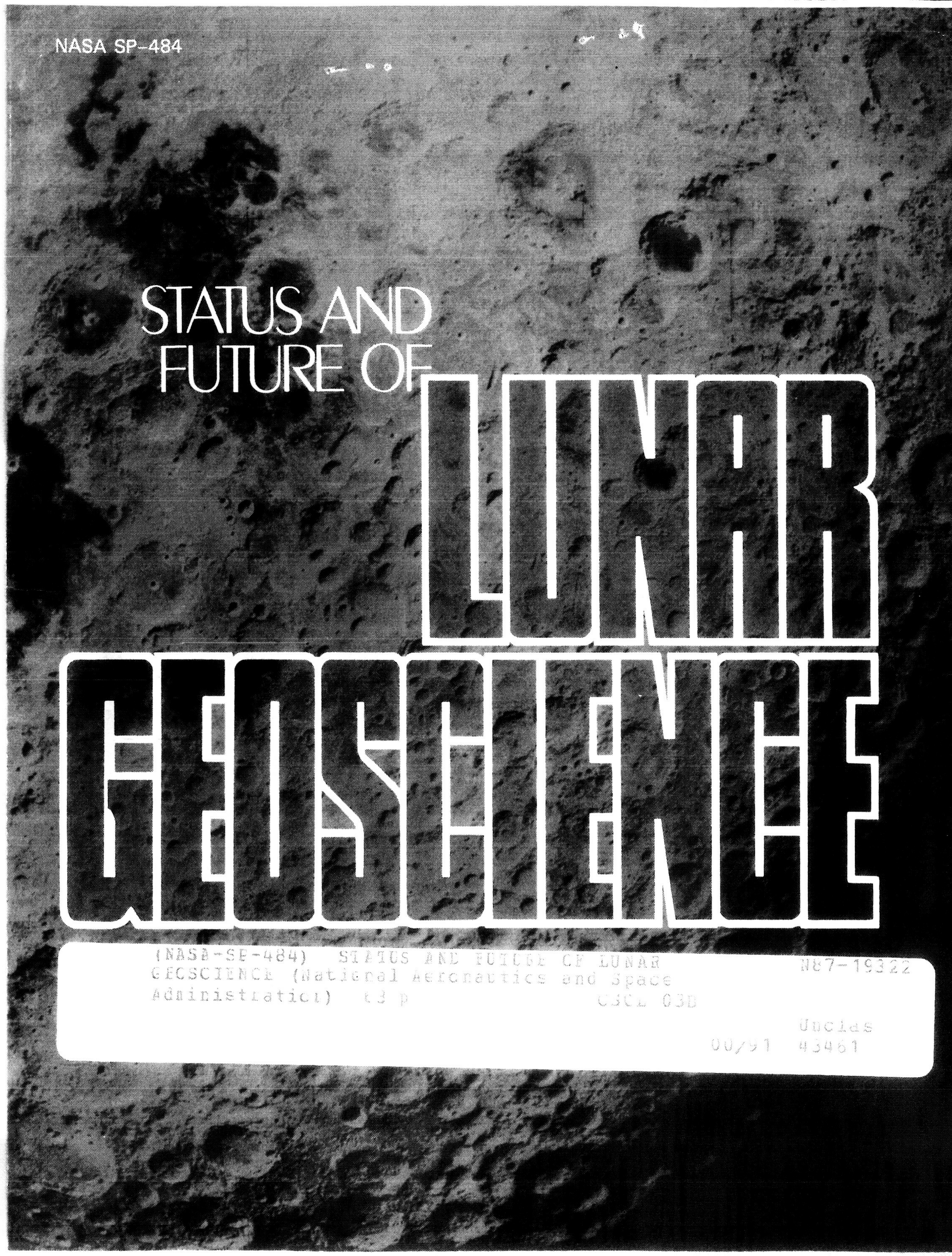
NASA SP-484

STATUS AND FUTURE OF LUNAR GEOSCIENCE



NASA SP-484

STATUS AND FUTURE OF LUNAR GEOSCIENCE

The Lunar Geoscience Working Group

P. D. Spudis, Chairman, *U.S. Geological Survey*
B. R. Hawke, *University of Hawaii*
L. L. Hood, *University of Arizona*
P. H. Schultz, *Brown University*
G. J. Taylor, *University of New Mexico*
D. E. Wilhelms, *U. S. Geological Survey*

Ex Officio

D. H. Scott, *U.S. Geological Survey*
S. C. Solomon, *Massachusetts Institute of Technology*

NASA Scientific and Technical Information Branch 1986
National Aeronautics and Space Administration
Washington, DC

Library of Congress Cataloging-in-Publication Data

The Status and future of lunar geoscience.

(NASA SP ; 484)
1. Lunar geology. I. United States. National
Aeronautics and Space Administration. Lunar Geosciences
Working Group. II. Series: NASA SP ; no. 484.
QB592.S73 1986 559.9'1 86-8626

For sale by the Superintendent of Documents,
U.S. Government Printing Office, Washington,
DC 20402

FOREWORD

What good is the Moon?

Does this question sounds familiar? It should. It has been asked for centuries, ever since humans realized that the Earth's nearest planetary neighbor was not a deity but another world.

Until a generation ago, the Moon was a distant, inaccessible world, lacking air, water, and life. It was hard to imagine that the Moon could be of much value even if it were possible to reach it.

Things have changed. Humans have travelled to the Moon, walked on it, set up instruments on it, and brought pieces of it back. We have learned more about the Moon in the last generation than in all of recorded history. In the process, the Moon may have become the unintended victim of our own success, for now we hear that the Moon is too close, it's too easy to get to, we've been there, we already know too much about it, there's nothing left to discover, and it's an uninteresting place compared to, for example, the nucleus of a comet or the moons of Uranus.

The result has been to leave the Moon deserted for more than a decade. No mission, manned or unmanned, has been launched to the Moon by any nation for more than 10 years.

In such an atmosphere of general neglect, this report is both important and long overdue. It describes clearly what we have learned about the Moon, so that any technically minded reader unfamiliar with the past generation of lunar research can learn, quickly and easily, how much we have learned and how far we have come. More important, the report also points out what we haven't learned about the Moon, what we still need to learn, and how we can go about learning it.

It is impossible to read this report and still believe that to study the Moon is to neglect the rest of the solar system. The Moon is a special world that preserves the early history of the solar system, and it is the key to understanding how all the terrestrial planets formed. There is a special local interest as well: the origin of the Moon is inseparable from the origin of Earth, and that bright familiar world in our own sky has a special importance for what it can reveal about the origin of our own planet and ourselves.

But our familiarity with the Moon is new, and our knowledge base is freshly minted. Readers under 30, who may not remember when it was impossible to go to the Moon, should try to imagine a time when everything we knew about the Moon was based on low-resolution remote sensing, numerical models, and speculation, all carried out by a small number of largely ignored scientists. We couldn't even

see half of the Moon, we couldn't tell what it was made of, and we had no idea whether it was young or old. To explain any observed lunar phenomenon there were a variety of theories, all of them untestable, and most of them wrong.

How suddenly all that changed! "Tranquillity Base here. The Eagle has landed." "That's one small step for a man. . ." With the return of the first 25 kilograms of lunar rocks and soil to Earth on July 24, 1969, we were flooded with data about the composition, age, and history of the Moon. Old questions were finally settled and new ones raised.

After Apollo, the Moon will never be the same again. It has become an individual world, with its own set of individual characteristics:

Dryness. The Moon, much to the surprise of almost everyone, has absolutely no water. Even the returned rocks contain no water, unlike almost all terrestrial rocks.

Lifelessness. There is no life, living or fossil, on the Moon. Even such essential chemical elements as carbon and nitrogen are lacking. (There is more carbon brought to the Moon in the solar wind than there is in the Moon rocks themselves.)

Diversity. The Moon is not a homogeneous world. Its surface is made up of a wide range of rock types. There are dark-colored volcanic lavas on the dark *maria* and lighter-colored aluminum-rich crystalline rocks in the highlands. There are also complex *breccias,* fragmental rocks produced by ancient meteorite impacts.

History. The Moon is not a primordial unchanged object like a meteorite. It is an evolved planet, with a unique geological history that has been traced by dating the returned samples. The oldest lunar rocks go back to the formation of the solar system 4 1/2 billion years ago, and the Moon and Earth have been separate planets ever since. Since it formed, the Moon has been modified by widespread primordial melting, intense meteorite bombardment, internal heating, and the eruption of vast floods of lava. For about the last 3 billion years, the Moon has apparently been quiet, and the seismometers placed on its surface by the Apollo astronauts showed that it is quiet now.

Surface Weathering. The Moon, even with no water or air, is continually "weathered" by the bombardment of its surface by large and small cosmic particles. This bombardment has gradually built up the *regolith,* a powdery layer that covers the Moon's bedrock. This layer has also trapped cosmic particles from the Sun (the solar wind) and the stars (cosmic rays).

Today's general picture of the "new Moon," established by the Apollo studies, is a far cry from the almost total ignorance of a generation ago. But this is not the whole story. The study of the Moon, like any other branch of science, has been a dynamic process, and one valuable feature of this report is to trace in detail how our understanding of the Moon has changed and grown since the last Apollo mission lifted off from Taurus-Littrow. There have been important (and unexpected) discoveries long after Apollo – the identification of lunar meteorites in the Antarctic, the still unexplained anomaly of nitrogen isotopes in the solar wind, and the discoveries of new types of lunar rocks. The original "magma ocean" concept, in which the Moon was once entirely covered by a thick layer of molten rock, is being critically evaluated using new data, with the result that the original "ocean" seems to be breaking up into an array of "seas" and "lakes." Finally, the fundamental (and still unsolved) problem – the origin of the Moon – is now being explored by a new theory involving a huge planetary impact on the still-forming Earth.

We now understand the Moon—and its future importance to science—pretty well. For today's scientists, the Moon is actually three different things: a museum world, in which the records of early planetary formation, now erased on Earth, have been preserved for study and understanding; a planet-sized laboratory in which we can study the effects of large-scale planetary processes—volcanism, meteorite impact, and magnetic field generation—in ways not possible on Earth; and a space probe, which samples the space environment and preserves billion-year records of the Sun and the stars.

The most amazing thing about this great mass of accumulated knowledge is that it has all been extracted from such a small part of the Moon. We have been much better at analyzing the Moon than at sampling it, and it is easy to forget just how meager our coverage of the Moon really is. The nine sampling sites (six American, three Russian) are all on the Moon's front side and are clustered along the equator. Orbital mapping, a major achievement of the Apollo program, is still woefully incomplete; the basic surface chemistry has been measured over no more than a fifth of the lunar surface, and geophysical information like magnetism and gravity is not much more extensive. Even though orbital imaging covers about 80 percent of the Moon, many important regions—particularly the lunar poles—are not defined in any detail.

With these huge gaps still remaining in our knowledge of the lunar data base, it is not surprising that lunar science still teems with mysteries and unanswered questions:

What is the origin of the Moon?

Why are lunar rocks magnetic when the Moon has no magnetic field?

What is the source of KREEP, the geological trace component which has such a critical effect on radiometric ages and petrogenetic modelling, but which has never been observed as discrete rocks or in specific surface locations?

What is the chemical composition of the whole Moon?

Why is the Moon asymmetric, with the volcanic lavas (*maria*) concentrated on the Earth-facing side?

Is the interior of the Moon still molten?

Does the Moon have a metal core?

How young are the youngest volcanic lavas on the Moon? How old are the oldest ones?

What process in the Sun caused the nitrogen-15 anomaly in the solar wind detected in samples of lunar soil?

Recently, the accumulated knowledge—and the unanswered questions—about the Moon have taken on new meaning in light of recent discussions about whether the Moon could support future space activities by providing resources or even permanent settling space for humans. In this debate about our future in space, the unanswered scientific questions about the Moon take on a new dimension: the answers are now needed by space planners, engineers, and future astronauts as well as by scientists. Some of the questions, in which science merges with engineering and economics, are:

Is there frozen water in the permanently shadowed regions of the lunar poles?

Are there undiscovered lunar rock types with unusual chemistries?

Are there geological processes on the Moon that concentrate important chemical elements such as useful metals?

What is the physical and chemical nature of the lunar regolith? What is its gas content?

What would be the best methods for extracting and fabricating useful materials from lunar rocks and soil?

The current discussions about the future use of the Moon do not reduce the Moon's already established scientific importance. Instead, these discussions provide a new sense of urgency to our scientific study of the Moon. It is now clear that scientists and space engineers must meet, and cooperate, in Moon research. Before we can plan lunar bases, even before we can be sure that lunar bases *can* be planned and successfully established, these questions—and many like them—must be answered.

Think about this report the next time you look up to see the Moon in the night sky. The Moon is not just an object, it is a world rich in both scientific and human potential. It contains a wealth of important scientific mysteries, many of them unknown and awaiting discovery. The Moon is a key to understanding the processes that have shaped the other planets and their moons. It holds a record of the history of the solar system, of our own essential Sun, and of the birth and death of distant stars. But the Moon is more than a world to study and learn from. It is a world we can *use*: a mine and factory to sustain major human activities in space, a site for permanent human habitation and a platform for the expanded study of the universe, and a way station to the planets beyond.

We cannot leap instantly into a future of space habitations, lunar bases, and human voyages throughout the solar system. We can reach such great goals only by taking small steps in the present. The next steps are clear, and we can plan them on the basis of the knowledge that is our legacy from the Apollo Program and the scientific studies that have followed it. Unmanned spacecraft like the Lunar Geoscience Orbiter can complete the global lunar observations only begun by Apollo. Unmanned sample return missions (successfully carried out by the Soviets more than a decade ago) can extend sample collecting to new areas and to unanswered questions. Lunar rovers (like the Soviet Lunakhods) can provide surface traverse data. At some point in this sequence, humans can return to the Moon, to study it in detail, to set up instruments on it, and to live on it.

What good is the Moon? Potentially, it is a scientific treasure house and a great economic resource to humanity. We'll never really know if we don't go back to find out.

Geoffrey A. Briggs
Director, Solar System
Exploration Division
NASA Headquarters

Acknowledgments

We thank David H. Scott, currently Discipline Scientist for the NASA Planetary Geology and Geophysics Program, for conceiving the idea of this working group and for providing logistical support. Helpful suggestions and encouragement were provided by M. B. Duke, J. W. Head, R. Phillips, S. C. Solomon, and L. A. Taylor; constructive reviews of the paper were provided by P. A. Davis, J. W. Head, S. C. Solomon, L. A. Taylor, and especially O. B. James and G. Ryder. We thank M. Kipp, B. K. Lucchitta, J. Melosh, and G. Ryder for providing figures.

CONTENTS

INTRODUCTION

WHY DO WE STUDY THE MOON?

There are three main reasons for lunar geoscience investigations. First, the Moon is a baseline for understanding the early history and evolution of the terrestrial planets and many satellites of the outer planets. The Moon possesses a differentiated crust and an ancient surface that have been well preserved since the first few hundred million years of solar system history. These characteristics and the Moon's relative accessibility make it an advantageous laboratory for studying early planetary evolution in the inner solar system. Although considerable understanding of the early Moon and solar system has been achieved using the Apollo database, this report will demonstrate that fundamental problems such as lunar crustal composition and genesis, geologic history, mantle composition and structure, nature of a possible metallic core, and thermal history remain only partly resolved. A continuing effort to describe and understand this relatively simple member of the terrestrial planets will expand our fundamental knowledge of planetary evolution.

A second reason for lunar geoscience investigation is to determine the Moon's origin. The Moon and Earth are closely related. Pinpointing lunar origin could yield knowledge of the dynamical and accretional processes that produced Earth in particular and the terrestrial planets in general. One dynamically plausible model of the origin of the Moon is that material ejected during the impact of a large planetesimal on Earth accreted in Earth orbit during the final stages of solar system formation. Another dynamically plausible model is the binary accretion hypothesis in which the Moon formed from iron-depleted planetesimals, which were never actually part of Earth, in Earth orbit. Continued studies of lunar bulk composition, dynamical modeling, and impact mechanics are needed to establish the mode of lunar origin and its relation to that of Earth.

A third motivation for the vigorous pursuit of lunar science is the Moon's proximity, making it central to many space applications. For space science, the lunar surface provides a record of the near-Earth space environment, allowing, for example, studies of the history of near-Earth meteoroid fluxes and energetic particle fluxes (solar and galactic cosmic rays). For human affairs, establishment of a long-term lunar base and utilization of lunar resources are inevitable, if not imminent, developments in the post-space station era. Geoscience investigations—including global geochemical, geologic, and geophysical mapping from a polar-orbiting satellite (the proposed Lunar Geoscience Observer)—will contribute to lunar resource evaluation and eventual manned lunar base site selection, as well as in-

creasing our understanding of lunar origin and evolution.

WHERE ARE WE NOW IN LUNAR SCIENCE?

Under the time pressures of six sample return missions within 3½ years and an annual program-mandated conference to report results, the early phases of lunar research were characterized by intensive data collection and publication of ideas. Such a fast-paced approach to science produced a plethora of ideas—some good, some charitably described as "exotic." At the same time that the initial examination phase of lunar study was giving way to a more thoughtful phase of data synthesis, funds for lunar research were gradually reduced. With less money available and insights harder to achieve, fewer people have been interested in carrying out lunar studies. The decrease in the number of researchers reduced the size of the audience for the results of lunar studies, which in turn caused more researchers to drop out. Some investigators seized opportunities to study other planetary bodies (such as Mars seen by Viking, and Jupiter and Saturn and their satellites by Voyager). Others who had analyzed Apollo samples turned to studying meteorites (e.g., isotopic anomalies) and terrestrial samples (e.g., kilometers of core drilled from Earth's ocean floor).

After more than 20 years of lunar study, we have found that the Moon defies attempts to "close the book" on it. Each advance has shown us a complex, fascinating planetary body whose complexity raises many more questions than are answered by those advances. The Moon offers us a perspective not only on its own evolution, but on the early histories of all the terrestrial planets and satellites of the outer planets. Despite the reduced number of active researchers in lunar science, the Moon still presents a vital, intellectually active field of inquiry, the results of which provide a more complete foundation for understanding the evolution of terrestrial planets. Continued advances in lunar science have been made possible by new technologies, fresh approaches to existing data, and radically changing conceptual frameworks. Lunar science is alive and well; some questions of lunar history have been settled, but far more significant questions remain.

WHERE DO WE GO FROM HERE?

Like the discipline itself, the next steps in lunar science are multifaceted. Because we continue to make progress with lunar data already in hand, we expect greater comprehension of the Moon from continued data production, analysis, and synthesis. We are acquiring new data by continued study of lunar samples and by Earth-based remote-sensing techniques. Ongoing research in terrestrial analogs (e.g., igneous and impact processes) and in laboratory experimentation (e.g., impact cratering and igneous petrology) modifies, clarifies, and expands our knowledge of lunar processes. Data returned from missions to other planetary bodies provide both information and new concepts that are directly applicable to lunar problems, and vice versa.

A major revolution in planetary science awaits us when we resume lunar exploration. Because the Moon is our information baseline for comparative planetology, sharpened understanding of lunar geologic processes and history will also expand our knowledge of the terrestrial planets. Lunar exploration should be given a much higher priority than it currently possesses. As a first step, a polar-orbiting spacecraft equipped with geochemical, geologic, and geophysical instrumentation should be flown as soon as possible. The proposed NASA Observer-class mission, the Lunar Geoscience Observer (LGO), properly augmented to carry as many instruments as possible, is a logical next step in planetary exploration. Subsequent missions should include unmanned sample returns and the emplacement of unmanned global geophysical networks. All of these potential missions would culminate with the return of humans to the lunar surface and eventual permanent lunar habitation.

STATUS AND UNRESOLVED PROBLEMS OF LUNAR SCIENCE

CHANGING PERCEPTIONS IN LUNAR SCIENCE

Lunar science did not end with Apollo (table 1); the last decade has witnessed an unmistakable gradual evolution and a few radical revisions of ideas in lunar science (table 2). The evolution was more a change in the perception of lunar processes and history than a dramatic increase in new data. Many of the relevant questions had been raised by 1975, but resources and time were not always available for detailed studies. The change in perception was driven by rethinking of critical issues, by greater appreciation for the exceptions as well as the norm, by renewed relevance provided by planetary missions, by new analyses of Apollo and Luna samples and data, and by new technologies. Even so, discoveries have been made during the last decade: lunar meteorites, evidence for widespread ancient mare volcanism, the association of geologic features with strong magnetic signatures, and others to be described here. Such changes in perception or new discoveries are fundamentally important; they are not simply small changes in our understanding. Many of them would have stimulated vigorous debate during the heyday of Apollo.

The following sections offer examples documenting significant progress in lunar science in the post-Apollo era. The examples illustrate the continuing progress in lunar studies that is sometimes overshadowed by new leaps in knowledge provided by other planetary missions.

SURFACE AND CRUSTAL GEOLOGIC PROCESSES

Cratering History

The lunar highlands display a heavily cratered surface. Deciphering the early cratering history of the Moon requires the proper interpretation of Apollo highland samples in relation to their geologic units. Relatively certain ages are available for the Imbrium Basin (3.85 billion years; Basaltic Volcanism Study Project, 1981, and references therein) and Serenitatis Basin (3.87 billion years; Winzer et al., 1977). The cluster of highland rock ages within the interval between 4.0 and 3.8 billion years ago and pre-Apollo ranking of relative ages of basins (Stuart-Alexander and Howard, 1970) suggested to Tera et al. (1974) that all lunar basins formed in this rather narrow time interval, for which they coined the term "terminal cataclysm." Subsequent study of the relative ages of lunar basins

Table 1. Pre-Apollo problems of lunar geoscience (as listed by site selection committees)

Problem	Status in 1959	Status in early 1969
Surface processes		
Surficial material	Volcanic ash, impact debris, or bare rock?	Impact debris (characterized by Surveyor)
Cratering	Impact or volcanism?	Majority impact; unknown percentage volcanic
Basin formation	Same as maria?	Giant impacts
Mare formation	Impact or volcanic?	Probably basaltic volcanism
Tectonism	Importance unknown	Many grooves and scarps considered tectonic
Surface composition	Unknown	Probably basalt and anorthositic gabbro (Surveyor)
Bulk composition	Iron poor, based on density	No progress
Heterogeneity		
Horizontal	Unknown	Probably heterogeneous
Vertical	Unknown	Probably differentiated
Primitive material	Unknown	Unknown; probably not commonly exposed
Geophysical properties	Unknown	Large circular maria are mascons
Organics and volatiles	Unknown	No progress
Rock ages	Unknown	Uncertain; probably ancient
Origin		
Time	Same as meteorites?	No progress
Mode	Captured, derived from Earth, or dual planet?	No progress

(Wilhelms, in press) has shown that the Apollo missions sampled only the youngest basins; many basins predate the Nectaris Basin, for which Apollo 16 data may have provided an absolute age (3.92 billion years; Maurer et al., 1978; James, 1981; Spudis, 1984). However, the present data do not allow us to resolve the issue of a terminal cataclysm. We need future sample return missions to obtain absolute ages for many lunar basins.

The cumulative bombardment history of the lunar highlands has been extensively studied (see review by Grieve, 1980). The observed high crater density may indicate that the highlands are saturated with large (> 100 km) craters (Hartmann, 1984). Other workers have suggested that the saturation diameter is much smaller (< 10 km; Woronow et al., 1982). A major advance toward understanding the nature of the cratering record of the highlands has come from the recognition that many craters are not primary, but are basin secondary craters (Schultz, 1976a; Wilhelms, 1976; Wilhelms et al., 1978; Eggleton, 1981). Moreover, volcanic resurfacing on the Moon prior to 3.9 billion years ago (Hartmann and Wood, 1971; Schultz and Spudis, 1983) had important effects on the observed highland cratering record (Hartmann, 1984). Our knowledge is not yet complete, but major progress has been made toward understanding early lunar cratering history.

The cratering record provides a means of determining the relative ages of surface units younger than the Imbrium Basin. Before and during the lunar landings, three different statistical techniques were used to estimate relative ages of surfaces from crater characteristics: relative position of the crater production slope (Shoemaker, 1965; Trask, 1966; Gault, 1970), transition from the crater production curve to the crater equilibrium curve (Trask, 1966; Shoemaker et al., 1969; Gault, 1970), and the relative degradation of craters at a given or normalized size (Soderblom, 1970; Soderblom and Lebofsky,

Table 2. Status of post-Apollo problems—1975 to 1985 (opinion of majority of workers)

Problem	Status in 1975	Status in 1985
Surface history		
Ancient cratering	Cataclysm popular	Gradual decline, with spikes
Later cratering	Constant or declining?	Substrate effects recognized
Mare volcanism	Mostly 3.8 to 3.1 billion years ago	4.2 to about 1.0 billion years ago
Surface processes		
Impact mechanics		
Craters	Scaling laws	Explosion, experimental and terrestrial craters helpful
Basins	Original depth, origin of rings?	Interplanetary comparisons helpful
Melt fraction	Considered small	Much melt, including ejected
Impact effects		
Secondaries	Mostly small	Basin secondaries abundant
Primary or local ejecta sampled?	Primary and local substrate mixing	Variable amounts of local rock
Regolith	Thicknesses estimated; core depositional record very complex	Core depositional models and maturity indices developed; evidence for variable solar activity
Megaregolith	2 to 3 km thick	Variable; possibly very thick (> 10 km)
Volcanism		
Mare flow thickness	Thin, fluid flows	Both thin and thick possible
In terrae	None likely	Some possible
Tectonism		
Mare loading	Recognized as mascon cause	Modeled
Modification of craters, basins	Uplifts recognized	Modeled
Effect of basins	Lithospheric thinning	Modeled
Crust		
Petrogenesis		
Magma ocean	Total melt of 100's of km	Magma ocean followed by serial magmatism
Primary rock types	Represented by glass types	Represented by pristine clasts
KREEP	Formed in Imbrium-Procellarum area?	Probably global
Structure		
Compositional layers	Not identified	Anorthositic "layer" above noritic "layer"?
Seismic	Upper 20-25 km layer of basalt?	20-25 km layer in terrae rock
Gravity	Preliminary modeling	Modeling still insecure
Mantle		
Seismic profile	Modeling uncertain with depth	Density probably increases with depth
Basalt source regions	Stratification uncertain	Heterogeneous at fine scale
Volatiles	Existence uncertain	Characterized from glasses
Core (metallic)	< 500 km radius	No progress
Global properties		
Moment of inertia	Still uncertain (close to 0.4)	0.3905 ± 0.0023
Heat flow	About 4 times Earth's?	About 2 times Earth's?
Paleomagnetism	Rock: not understood	Rock: not understood Orbital: bright swirls, highly magnetic
Bulk composition	Preliminary estimates	Improved estimates
Origin of Moon	Oxygen-isotope data indicate close relation between Earth and Moon	Giant impact on Earth followed by coaccretion favored

1972; Boyce, 1976). The relative ages could be converted to absolute ages using lunar sample data. Some prelanding predictions based on crater statistics and the observed meteor flux rate proved to be grossly in error, which increased the caution—if not skepticism—used in applying crater statistics to surface dating. Nevertheless, within reasonable limits, crater statistics for each landing site have permitted interpolations and extrapolations to unvisited sites with some confidence. The short time between each mission from 1969 to 1972 was insufficient for the reanalysis and synthesis necessary to reconcile contradictions or inconsistencies among or within different techniques.

Advances have been made in understanding the complexities of crater statistical data. At the fine scale (craters less than 1 km in diameter), the importance of substrate strength has been documented for both crater production (Lucchitta and Sanchez, 1975; Schultz and Spencer, 1979) and crater destruction (Lucchitta and Sanchez, 1975; Young, 1975; Schultz et al., 1977; Chapman et al., 1979). This work helped to reconcile prelanding predictions of surface ages and specific limitations in the various techniques. Other variables that may be important include nonrandom contributions by secondary impact (Shoemaker, 1965; Gault, 1970), surface lighting conditions (Young, 1975, 1984), resurfacing by thin lava flows (Greeley and Gault, 1970; Neukum and Horn, 1976), and possible changes in the size distribution of impacting objects with time (Moore et al., 1974; Strom and Woronow, 1982). Many of these variables were anticipated before the lunar landings ended (Chapman et al., 1970) but could not be studied specifically until the post-Apollo period of analysis.

In addition to absolute ages determined at the nine sampled landing sites, absolute ages of five other features have been inferred: Copernicus (Silver, 1971), Tycho (Drozd et al., 1977), Cone Crater, South Ray Crater, and North Ray Crater (Burnett and Woolum, 1977). These 14 calibration points permit us to address problems such as possible changes in the flux rate with time (Neukum et al., 1975; Guinness and Arvidson, 1977) and age extrapolation for other unsampled surface units (Boyce, 1976; Neukum et al., 1975; Schultz and Spudis, 1983).

The view of crater statistics in lunar science has changed considerably over the last decade, largely because of continued studies that demonstrate the consistency of the results within reasonable limits and that identify specific factors that can affect direct application of the data. The need to understand lunar crater statistics is as important for the calibration of similar data for other planetary bodies as it is for the resolution of lunar geologic history.

Cratering Mechanics

Manned lunar landings and returned samples stimulated great interest in impact cratering. Lunar samples had to be interpreted in the context of shock processes (e.g., sample provenance, regolith evolution, breccia formation, and geochronology). Further, the creation of major landforms and the evolution of the surface are intimately tied to cratering mechanics. Before 1975, the perception of impact mechanics was dominated by somewhat intuitive extrapolations from explosion analogs, laboratory-scale cratering, terrestrial craters, and observations and measurements of lunar craters. Several examples of the status of cratering mechanics and their implications in 1975 follow. The emplacement of ejecta deposits around large craters was widely viewed as a simple blanketing by debris; however, the high impact velocity of such debris indicated that this analogy was an oversimplification. Also, numerical finite-element computer codes detailing the mechanics of excavation were just beginning to be adapted after decades of experience with explosion cratering, but work showing appreciation of the differences and similarities of explosion and impact cratering remained mostly unpublished. Terrestrial impact craters also provided fundamental information for cratering mechanics, but the possible effects of the terrestrial environment were difficult to evaluate without the broader perspective provided by other planetary missions. Finally, remote-sensing techniques (Earth-based spectroscopy and orbital geochemical data) were just being refined and

calibrated to the point at which the data could be better understood.

Although significant advances in cratering mechanics have been made over the last decade, perhaps greater advances have been made in the application of impact processes to a variety of specific lunar problems. Cratering flow fields have been predicted through theory (Orphal et al., 1980) and documented through experiments (Stöffler et al., 1975). Models of cratering flow fields using assumptions about crater scaling (Ivanov, 1976; Schultz and Mendell, 1978) and laboratory experiments (Gault and Wedekind, 1977; Schmidt and Holsapple, 1980) began to demonstrate the effects of gravity on large-scale events. Borrowing from explosion-cratering studies, numerous researchers explored simplified analytical approximations of the cratering flow field, called the Z-model (Maxwell, 1977; Orphal, 1977a, b), to describe aspects of the impact process (Croft, 1980, 1981a; Thomsen et al., 1979; Austin et al., 1981; O'Keefe and Ahrens, 1981; Grieve and Garvin, 1984). The Z-model provides a reasonable and useful description of crater growth during the later stages, that is, after most of the kinetic energy of the impactor has been transferred to the target. A more generalized analytical description of crater growth has been formulated (Holsapple, 1981) that links initial stages, when the impactor transfers energy to the target, with later stages, when a flow field similar to the Z-model has been established.

The Z-model proved useful for predicting final crater dimensions for explosion cratering. For lunar impact cratering, it has been more useful for its semiquantitative analytical description of crater flow fields, as it has helped in interpreting the provenance of lunar samples (fig. 1; Croft, 1980; Stöffler, 1981) and modeling the excavation of multiring basins (Croft, 1981a, b; Spudis et al., 1984). Implications for the depth of derivation of lunar samples are that samples ex-

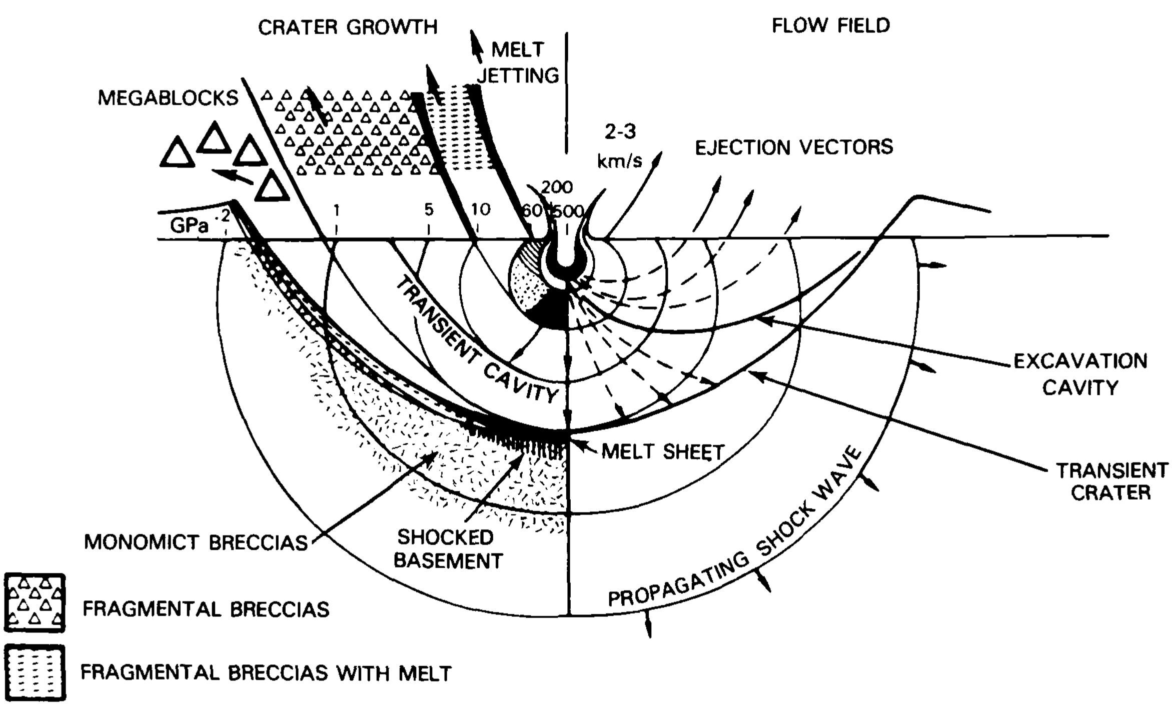


Figure 1. Schematic drawing of excavation stage of crater formation. Dashed lines on right (flow field) show paths of particle movement predicted by the Z-model. Symbols at left show provenance of crater-ejecta types within crater transient cavity. Numbers indicate peak shock pressures in gigapascals (GPa). From Stöffler (1981).

cavated by simple, bowl-shaped craters (up to 15 km in diameter on the Moon) are derived from depths of less than about one-tenth the diameter of the source crater (fig. 1). Modeling basin excavation depths is less certain, because of the difficulty in establishing the original transient-crater diameter and extrapolating the flow field to basin scales. If basin transient cavities grow in the same manner as small craters (proportional growth), then maximum depths of excavation of 40 to 80 km are indicated for the largest basins. However, such modeling further indicates that greater than 90% of the ejecta volume from a basin impact is derived from depths of less than about 30 km in the lunar crust. Thus, such models and supporting sample data suggest that little lower crustal or mantle material is ejected during basin formation.

The effect of gravity on both the cratering flow field and crater modification has gained wider appreciation. Experimental studies for $g < 1.0$ (Gault and Wedekind, 1977) and $g > 1.0$ (Schmidt and Holsapple, 1980) provided data necessary for extending scaling relations not only to different planetary bodies, but also to basin-sized impacts. Studies of impacts into strengthless targets (Gault and Sonett, 1982; Fink et al., 1984) documented the process of crater collapse. Although the effect of gravity on crater growth was recognized before 1975, the last decade has witnessed its incorporation in a wide variety of models of large-crater and basin formation and greater appreciation for the distinction between the gravity-controlled excavation cavity and the strength-controlled collapse zone (Ivanov, 1976; Croft, 1981a, b; Grieve et al., 1981; Schultz et al., 1981). Such studies have been aided by detailed topographic and gravity data for craters and basins on the Moon and Mercury (Gault et al., 1975; Cintala, 1979; Pike, 1980; Bratt et al., 1985).

In summary, the general view of the cratering flow field has evolved over the last decade from intuitive or analog models to analytical descriptions that have been applied (in principle) over a broad range of dimensions, from the provenance of Apollo 16 samples excavated by the events which formed North Ray and South Ray Craters to the interpretations of samples excavated by the Imbrium Basin impact event.

Cratering Effects

Crater and basin ejecta

Better understanding of the cratering process provided a greater appreciation of cratering effects, including ejecta emplacement (fig. 2) and global disruption. One of the major controversies in cratering studies 10 years ago was the mode of emplacement of the ejecta from large craters and basins (see Oberbeck, 1975, and Chao et al., 1975). The controversy centered on the effects of relatively high-velocity (0.2 to 1.0 km/s) ejecta impacting the surface. Experimental, theoretical, and lunar sample studies and terrestrial field studies all indicated that the impact of such ejecta must reexcavate considerable preexisting materials, thereby drastically modifying the view of an "ejecta blanket" (Oberbeck, 1975; Morrison and Oberbeck, 1978; Hörz et al., 1983). This concept has gained wide acceptance and provided the context for numerous mixing models intended to explain spectral and geochemical data (Hawke and Head, 1978; Pieters et al., 1985), but it has been challenged on the basis of lunar geologic mapping and new experimental results (see James and Hörz, 1981). Specifically, Schultz and Gault (1985) have argued that near the rim the ejecta curtain is composed of fragmental debris that impacts over a finite time, thereby resembling the impact of a cluster rather than a discrete projectile. Farther from the rim, impact of discrete ejecta would provide results similar to the model by Oberbeck (1975), whereas impact of clusters of ejecta would decrease the amount of locally excavated debris. Moreover, Schultz and Gault (1985) argued that identification of ejecta responsible for secondary cratering depends on both the dispersal of this component downrange and the competence of the target. The view of ejecta emplacement, therefore, may be shifting from the individual concepts of either simple blanketing or local mixing to a more general combination of the two.

Some aspects cannot be completely addressed by simple analytical models of crater growth; such aspects include the generation and distribution of impact melt and vapor, unusual impactor composition and physical state, and the

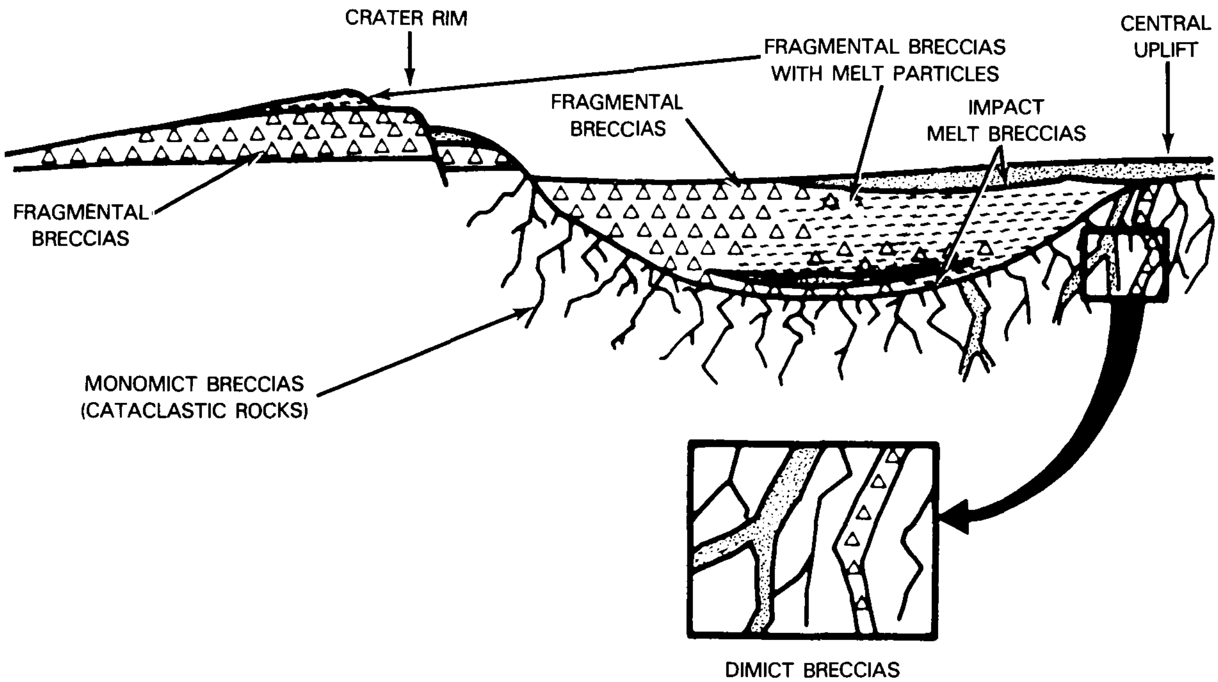


Figure 2. Schematic cross-section through a complex crater showing the geologic setting of impact ejecta. From Stöffler (1981).

role of postimpact crater modification. The available advanced finite-element computer codes indicate that only half of the generated impact melt is excavated from the cavity (Orphal et al., 1980). Moreover, the shock level of material may vary widely at any given distance from the crater, although the minimum shock level increases with distance (Schultz et al., 1981; Hörz et al., 1983). Such conclusions are consistent with detailed analysis of shocked materials in laboratory impact craters in sand (Stöffler et al., 1975), where 85% of the shock-metamorphosed particles remain in the cavity. The view of impact-melt generation and deposition has evolved over the last decade. The rapid quenching of impact melt deduced from lunar sample studies and large terrestrial impact craters raised serious doubt as to the existence of fluidlike impact melt within and outside lunar craters. However, the presence of impact melts around lunar craters is consistent with photogeologic identification of impact-melt flows and ponds around lunar craters (Howard and Wilshire, 1975; Hawke and Head, 1977), observations of the thermal properties of these units from the Apollo orbital infrared scanning radiometer data (Schultz and Mendell, 1978), and the distinct morphology of small fresh impact craters on young melt sheets, such as the King Crater melt sheet (Schultz and Spencer, 1979).

The apparent contrast between the lunar and terrestrial cratering records is not yet fully understood. Detailed syntheses, such as those of Kieffer and Simonds (1980), Grieve et al. (1981), Hörz et al., (1983), and others, however, help to describe crater formation on Earth, while complementary theoretical studies (Roddy et al., 1980; O'Keefe and Ahrens, 1981), analytical models (Melosh, 1981), and experiments (Schultz and Gault, 1979; Gault and Sonett, 1982) help to identify conditions perhaps unique to Earth.

The lunar regolith and the Sun's history

One of the great hopes before and during the Apollo missions was that the lunar surface would

contain a record of the Sun's history. By the end of the missions, several studies of a variety of nuclear effects had resulted in the general conclusion that the Sun's activity (on a million-year time scale) has been virtually constant for the past 4 billion years. Recent research has demonstrated that this conclusion was premature. The work on isotopic effects was accompanied by detailed studies of the petrologic, physical, and chemical nature of the lunar regolith. This work has been essential in understanding the solar record and has also contributed to the reliability of remote-sensing measurements of the lunar surface.

Although regolith processes were beginning to be understood soon after the Apollo landings, the general view was that the lunar regolith was a chaotic, impossibly complex pile of rubble. The developement of fairly detailed Monte Carlo models for regolith gardening and mixing brought some order to the chaos and put the detailed information about individual soil and core samples into a rational (although complex and stochastic) context (Hörz, 1977).

The longer a volume of regolith is exposed at the lunar surface, the more mature it becomes. Maturity indicators were proposed during the missions, but it was not until 1977 that we began to understand the maturation processes. An important part of this understanding was the establishment of the ratio of fine-grained metal content to total iron oxide (FeO) as a generally applicable maturity index (Morris, 1978). This new concept of soil maturity was essential in the development of regolith deposition models. Analysis of lunar core samples established that the structure of the regolith is incredibly complex. Each core reflects a unique depositional history. Depositional histories of the sections of regolith sampled by the cores clearly involve multiple stages and pervasive mixing processes. Nevertheless, self-consistent depositional models have been worked out (Bogard et al., 1980). Such models are essential to a study of the Sun's history.

A major discovery of post-Apollo lunar sample studies was the exciting evidence for a substantial secular variation in the ratio of ^{15}N to ^{14}N in the solar wind. Recent work has led to the conclusion that the increase in $^{15}N/^{14}N$ is probably due to nuclear reactions in the Sun (Clayton and Thiemans, 1980). The details of these reactions have not yet been worked out, but it seems clear that research is leading to a reappraisal of our ideas about solar evolution.

Analyses of xenon isotopes in lunar samples during the Apollo program showed that some of the older lunar rocks contained products of the radioactive decay of short-lived nuclear species (^{129}I and ^{244}Pu) that are now extinct in nature. Although these observations are a clear indication of the great antiquity of the Moon, they were at first puzzling in the context of specific rocks, which, while very old, still postdated the extinction of the ^{129}I and ^{244}Pu parent nuclides. An important conclusion of post-Apollo analyses was that the daughter xenon isotopes had been lost from the Moon's interior and then had been retrapped along with solar wind ions in ancient lunar soils. This conclusion has allowed us to estimate the age of solar wind implantation in these samples, which, in turn, has been used to show that the isotopic compositions of solar wind argon, krypton, and xenon have been virtually constant over the lifetime of the Moon, whereas helium and possibly neon, along with nitrogen, have been gradually enriched in relatively heavier isotopes (Pepin, 1980). Thus, the noble gas data suggest that solar wind variations were not unique to nitrogen, though they apparently were limited to light elements.

The megaregolith

A consequence of the early intense lunar bombardment was the brecciation of the highlands crust. This zone of comminuted, possibly chemically mixed, debris was given the name "megaregolith" (Hartmann, 1973) by analogy with the much thinner debris blanket that covers the lunar mare basalt flows. Both lunar crustal structure and sample provenance concepts depend on the estimate of thickness of the highlands megaregolith. One of the first comprehensive attempts to estimate this thickness was that of Short and Forman (1972), who considered the effects of the population of observable highlands craters having a diameter range of 3.5 to 500 km. They concluded that the minimum

thickness of the megaregolith is on the order of 1 to 2 km. A similar result was achieved by the more sophisticated Monte Carlo model of Hörz et al. (1976), who also noted, however, that these results are valid only if the currently observable highland crater population represents the cumulative bombardment history of the Moon. These model values (1 to 2 km) of megaregolith thickness have been used by workers attempting to understand such diverse problems as lunar tectonism (Golombeck, 1979), block distribution around highland craters (Thomsen et al., 1979), and lunar bulk composition (Rasmussen and Warren, 1985).

Recent studies have suggested that megaregolith thickness may be much greater than 1 or 2 km. A line of evidence leading to this idea was the establishment of a possible absolute age for the Nectaris Basin (3.92 billion years; James, 1981; Spudis, 1984). Using the crater frequency distributions for lunar basins compiled by Wilhelms (in press), Spudis (1984) suggested that the most densely cratered surfaces of the Moon are probably no older than 4.0 to 4.1 billion years. If this is so, then the currently observed crater population in the lunar highlands does not represent the total crater population, and the megaregolith thickness may be much greater than 1 to 2 km (Hörz et al., 1983; Spudis, 1984). Moreover, a new Monte Carlo model of megaregolith development (Cashore and Woronow, 1985) predicted mean thicknesses of 20 to 40 km. A thickness of tens of kilometers has profound implications for lunar thermal history, the interpretation of lunar seismic velocities and remotely sensed geochemical data, provenance of Apollo highland samples, and the survival of ore deposits in the terra crust. We must continue work on this important problem to understand fully the complexities of lunar geologic history.

Volcanism

Thickness of mare fill

Knowledge of the thickness of mare basalt is fundamental to determining the fraction of mare basalt in the crust, the degree of partial melting of the mare basalt source regions, the origin of mascons, and the thermal evolution of the lunar interior. The seismic velocities in the upper part of the crust in the Fra Mauro-Apollo 12 region (to depths of 20 to 25 km) are within the velocity range determined for lunar basalts, and this upper crustal layer was originally interpreted to be composed of material similar to the mare basalts returned from the lunar surface (Toksoz et al., 1972, 1973). This interpretation is consistent with the determination that a basaltic fill 15 to 20 km thick would account for the lunar mascons. Analysis of hummock height and regional slopes, as well as the existence of large (100 to 200 km in diameter) pre-Imbrian craters, led Head (1977) to conclude that the crust in this area has mare basalt less than 1 km thick, and that Imbrium ejecta is underlaid by impact-fractured rocks to depths of 20 to 25km. He suggested that the seismic velocity profile of the outer portion of the crust represents a progressively higher velocity downward in an anorthositic gabbro/norite crust due to a decrease in shock effects rather than to a mare basalt composition.

Subsequent work by Rhodes (1977), Hörz (1978), and De Hon (1979) has provided strong evidence that most mare deposits are relatively thin (< 1 km). Perhaps only in the centers of the large mare-filled impact basins do basalt thicknessess exceed 5 km (Head, 1981).

Thickness of individual mare-basalt flows

Opinions on the thicknesses of the various flows from which the mare samples were derived have varied radically over the past 15 years. During the early Apollo missions, it was proposed that the lunar maria had been very large, deep lava lakes and that the mare samples were crystallized from residual liquids erupted on the surface as secondary lava flows (O'Hara et al., 1970, 1975). Evidence against this hypothesis includes the following: (1) photogrammetric measurements of the youngest flow scarps in the Imbrium Basin indicate thicknesses of 10 to 30 m (Schaber, 1973); (2) later studies indicate that these young Imbrium flows are unusually thick and that the vast majority of mare lava flows are less than 10 m thick (Head, 1976; Schaber et al., 1976); (3) the range of ages determined for mare surfaces in the

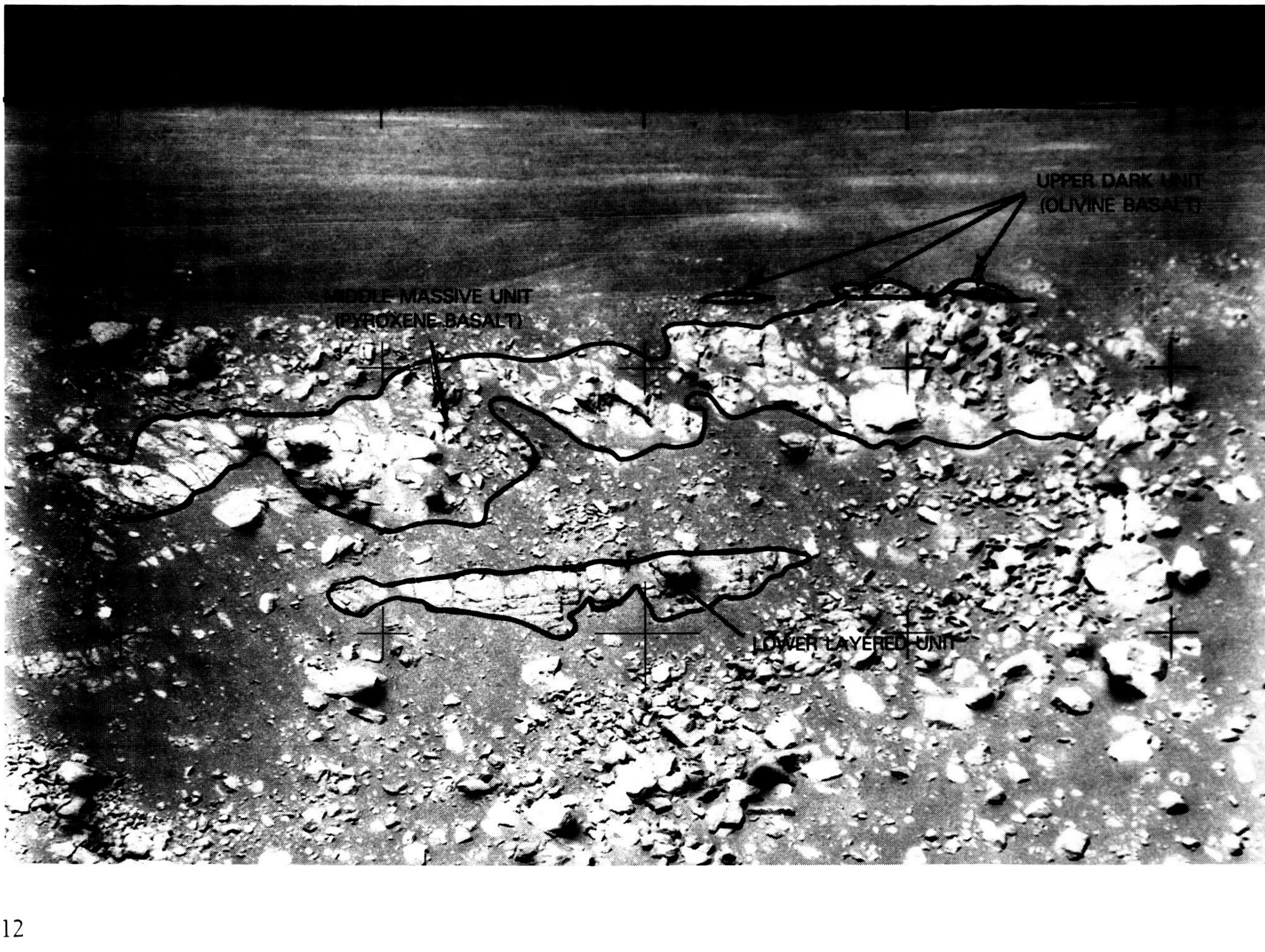
basins (Boyce, 1976) is much greater than would be expected from surfaces produced by multiphase eruptions of residual liquids from a large lava lake; (4) chemical kinetic experiments on natural and synthetic lunar basalts (Brett, 1975) and dynamic crystallization experiments (Grove and Walker, 1977) indicate that the Apollo 11, Apollo 12, and Apollo 15 mare basalts were derived from cooling units tens of meters thick, in apparent agreement with the photogeologic evidence; and (5) most basalt units photographed in the upper 60 m of Hadley Rille are massive, averaging at least 10 m in thickness, whereas other units are layered on a scale of several meters (fig. 3; Howard et al., 1972).

Duration of mare volcanism

A decade ago, most of the lunar science community agreed in general that mare volcanism was confined to a relatively short interval of internal heating that started about 3.9 billion years ago and ended before about 2.5 billion years ago (Taylor, 1975; Head, 1976). In recent years, a variety of evidence indicates that lunar mare volcanism was active from at least 4.2 billion years ago to perhaps as late as 1.0 billion years ago.

Recent photogeologic, spectral, orbital geochemical, and lunar sample studies document the importance of an epoch of mare volcanism before 4.0 billion years ago. Samples provide

Figure 3. West wall of Hadley Rille at Apollo 15 landing site. At least three mare basalt layers are recognized, the thickest of which (middle massive unit) is about 17 m thick. Rock types are inferred from sampling of similar outcrops on the east wall of the rille by astronauts. These direct observations suggest that individual mare basalt flows at the Apollo 15 site are relatively thin (NASA photo AS15-12157).



direct evidence for this ancient volcanism, but allow no estimate for its distribution and volume. Ryder and Taylor (1976) have presented arguments for mare-type volcanism before 3.9 billion years ago and demonstrated the occurrence of rare mare-type basaltic mineral and lithic fragments in highland breccias. On the basis of the ages of basaltic clasts in the Apollo 14 breccias, Hawke and Head (1978) concluded that high-alumina mare basalts were in the Fra Mauro region before the Imbrium impact (3.85 billion years ago). Ryder and Spudis (1980) concluded from a variety of lunar sample data that mare volcanism started well before the end of the heavy early bombardment (3.9 to 4.0 billion years ago). Taylor et al. (1983) presented data for basaltic clasts in Apollo 14 breccia 14305 that demonstrate that mare-type volcanism took place 4.2 billion years ago in the Fra Mauro region. One clast of ancient mare basalt yielded a rubidium-strontium internal isochron (crystallization) age of 4.23 ± 0.05 billion years.

Geologic and remote-sensing data provide evidence for the distribution of ancient mare volcanism. Hartmann and Wood (1971) suggested that some highlands plains were early upland volcanic floods, but specific evidence is not cited. Schultz and Spudis (1979) studied the distribution and composition of dark-haloed impact craters in the lunar highlands, most of which appear to have excavated dark basalt from beneath a higher albedo surface layer. They suggested that basaltic volcanism may predate the last major basin-forming impacts, that early far-side mare volcanism may have been widespread, and that some lunar lights plains are early mare deposits that were subsequently covered and reworked by impact ejecta. Near-infrared reflectance spectra (Hawke and Bell, 1981; Bell and Hawke, 1984) demonstrate that many dark-haloed impact craters excavated ancient mare units buried by basin and crater ejecta. Studies of the orbital geochemical data sets (Hawke and Spudis, 1980; Hawke et al., 1985) show that mafic geochemical anomalies on the east limb and far side of the Moon are commonly associated with light-plains deposits that exhibit dark-haloed craters; the ages of the plains units indicate that extrusion of mare basalt was a major lunar process well before 4.0 billion years ago. The distribution of dark-haloed impact craters led Schultz and Spudis (1983) to estimate that the minimum areal extent of these ancient mare deposits exceeds 7.5×10^5 km^2, or approximately 12% of the area of the post-Imbrium maria (fig. 4).

At the other end of the time scale, photogeologic evidence suggests that the youngest mare eruptions may have occurred about 1.0 billion years ago. Previous interpretations had dated the last stages of widespread lava flooding at about 2.5 ± 0.5 billion years ago (Boyce and Johnson, 1978) and the youngest eruptions at around 1.7 to 2.0 billion years ago (Boyce et al., 1974; Young, 1977). Schultz and Spudis (1983) showed that Lichtenberg Crater deposits are embayed by mare basalts emplaced about 0.9 billion years ago (fig. 5). In addition, they identified several small regions in Oceanus Procellarum and elsewhere on the Moon that seem very young (younger than 1.0 billion years).

Highland volcanism and the origin of light plains

Since the first manned mission to the Moon, considerable controversy has surrounded the nature, extent, and even the reality of highland volcanism. Part of the problem has been a misunderstanding or misuse of the phrase itself. "Highland volcanism" refers to the extrusion of magma of nonmare composition, not to the extrusion of small, isolated ponds of mare basalt in highlands terrain or to mare pyroclastic mantling deposits in highlands.

Before the Apollo 16 mission, several morphologic units in the lunar terra were thought to be volcanic in origin (Milton, 1968; Trask and McCauley, 1972). In fact, a major goal of the Apollo 16 mission was to sample units, including the Cayley plains, which were interpreted by some to be of volcanic origin. When examination of the Apollo 16 samples revealed that all were impact derived, most highland terrains previously interpreted as volcanic were reinterpreted as the products of impact processes (e.g., Howard et al., 1974). However, studies in recent years have provided evidence that certain units in the highlands are indeeed of volcanic origin. A prime candidate is the Apennine Bench Formation, a light-plains

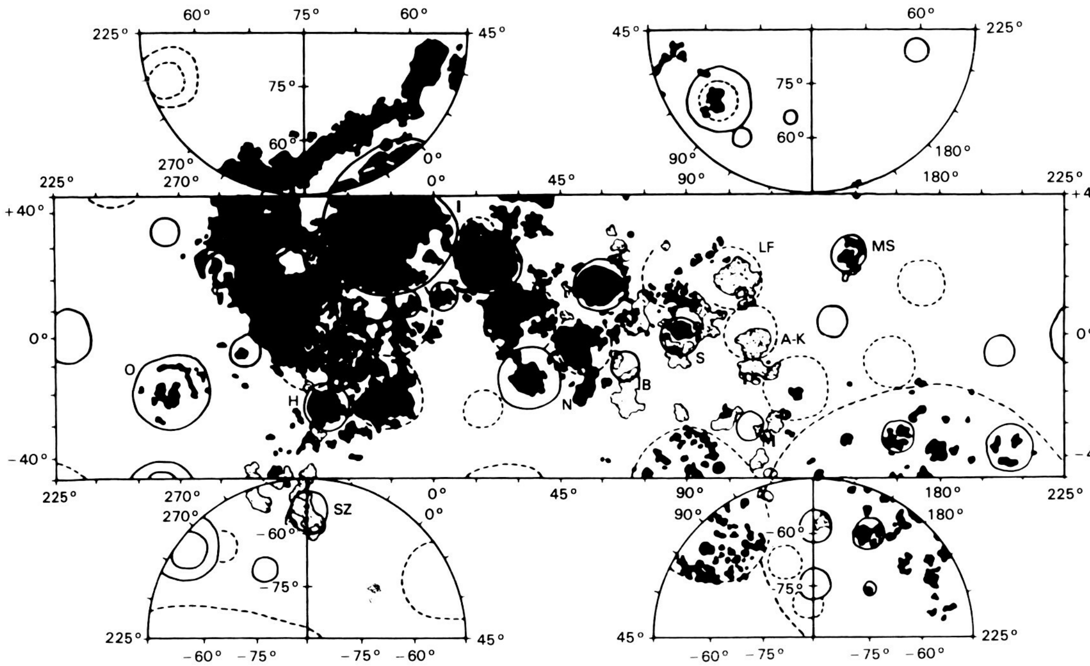


Figure 4. Map showing distribution of visible maria (later than 3.85 billion years ago; black) and old mare deposits buried by highland light-plains material (earlier than 3.85 billion years ago; stippled). The wide distribution of these ancient mare deposits suggests that mare volcanism was an important lunar process during the epoch of heavy bombardment (earlier than 3.85 billion years ago). Basins are indicated by solid and dashed circles. From Schultz and Spudis (1983). Basin names SZ, Schiller-Zucchius; LF, Lomonosov-Fleming; MS, Moscoviense; AK, Al-Khwarizmi-King; B, Balmer; N, Nectaris; H, Humorum; O, Orientale; I, Imbrium; S, Smythii, M, Milne; TS, Tsiolkovsky-Stark.

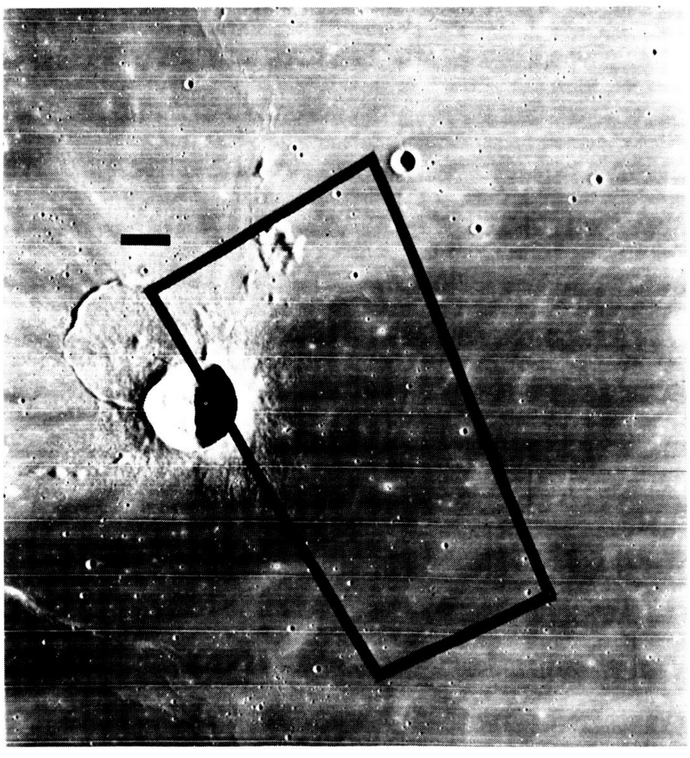


Figure 5a. Vertical view of bright-rayed, 20-km-diameter Lichtenberg Crater in northern Oceanus Procellarum. Southern and eastern areas outside the crater appear to be embayed by low-albedo mare basalt. The outlined area is shown in fig. 5b; north at top; bar width, 10 km.

deposit southwest of the Apollo 15 landing site (fig. 6). Orbital geochemical data demonstrate that this unit is composed of Apollo 15 KREEP basalt, and geologic evidence indicates that it was emplaced by extrusive igneous processes (Spudis, 1978; Hawke and Head, 1978; Spudis and Hawke, 1985).

Although the importance of nonmare volcanism in the evolution of the lunar highand crust is not known, it appears that at least one unit is of volcanic origin. Global maps of lunar surface chemistry and mineralogy are required to better assess the extent of highland volcanism.

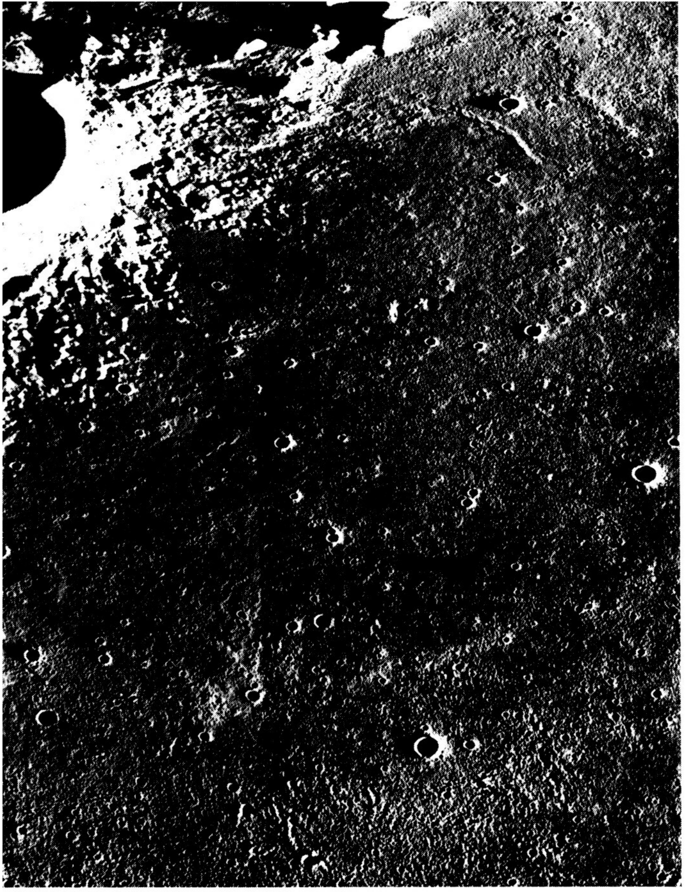


Figure 5b. Oblique high-resolution view of Lichtenberg Crater (top left). This view clearly demonstrates that Lichtenberg deposits are embayed by mare basalt flows; these lavas therefore postdate the crater. Comparison of crater density on these basalts with those of Copernicus Crater suggests an age contemporaneous with that of Copernicus, which is possibly less than 1.0 billion years old. These mare basalts are the youngest yet identified on the Moon. North at top; bar width, 5 km. From Schultz and Spudis (1983).

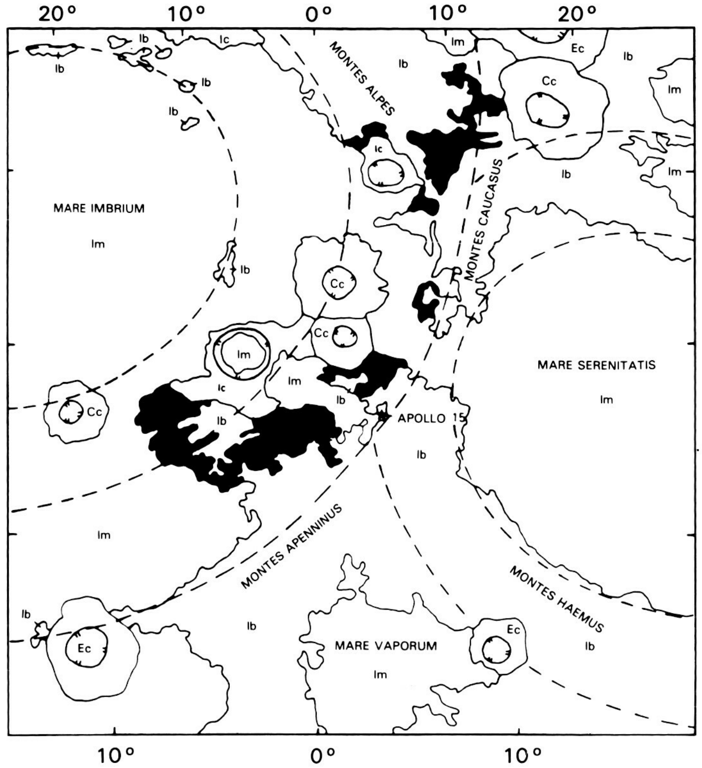


Figure 6. Regional geologic sketch map showing the distribution of the Apennine Bench Formation of early Imbrian age (black). Orbital geochemical data for this unit suggest a composition similar to Apollo 15 volcanic KREEP basalt. These plains are the largest recognized exposure of nonmare volcanic deposits on the Moon. Im, Imbrian mare material; Ib, Imbrian basin material; Ic, Imbrian crater material; Ec, Eratosthenian crater material; Cc, Copernican crater material.

CRUST

Petrogenesis

Igneous processes

Our understanding of processes that operated during the genesis and evolution of magmas has increased dramatically during the past decade. Not only have petrologists obtained more insight into processes such as partial melting and fractional crystallization, whose importance is well established, but there has also been a resurgence of interest in processes long cast aside as flights of petrologic fancy, or at least as not contributing significantly to the production of observed igneous rocks. Some of these refurbished ideas are magma mixing, liquid immiscibility, assimilation, the role of volatile and fluid transfer, and boundary-layer processes. Lunar research has contributed to the development of these ideas, especially of the first three (Stolper, 1979; Walker, 1983a).

The original idea of magma mixing was that two different primary magmas mixed to produce intermediate types. This extreme process was rejected long ago and has not been resurrected. However, a more modest version, the mixing of genetically related magmas, rather than drastically different, unrelated magmas, has been ac-

cepted. For example, a magma crystallizing in a magma chamber consists of both crystals accumulating near the bottom of the chamber and the still-molten portion that, due to crystallization and removal of early phases, has a composition different from that of the original magma. Injection of a new batch of fresh, unfractioned magma results in a mixed product that has a major- and trace-element composition unlike any that could be achieved by fractional crystallization alone. One of the first extraterrestrial applications of this concept was made by J. Longhi (Longhi and Boudreau, 1979; Longhi, 1980) to explain the diversity of rock types in the lunar highlands. This work highlighted the potential importance of magma mixing in producing suites of igneous rocks.

Lunar sample analysis can take most of the credit for revitalizing the idea that a silicate liquid can fractionate to a point at which it separates into two immiscible liquids. Clear evidence that this process occurs in nature was first observed in the mesostases of Apollo 11 basalts (Roedder and Weiblen, 1970). Petrologists still question the scale at which the process operates, however. Some lunar investigators have proposed silicate liquid immiscibility as a mechanism for producing some highly evolved lunar rock types such as granites (Hess et al., 1975; Roedder, 1978; Taylor et al., 1980). The potential importance of liquid immiscibility has been emphasized recently by lunar petrologists trying to understand the origin of mare basalts that have very high potassium contents, which have recently been discovered among the myriad of clasts in Apollo 14 breccias (Shervais et al., 1985).

Assimilation is the digestion of solid rock by a magma. In this case, lunar work has not driven the resurrection of this idea, but authors of models for the evolution of both highland and mare rocks evoke the concept to explain some otherwise baffling compositional trends. As in terrestrial petrology, assimilation is not simply the mixing of two extremes; it involves partial melting of the contaminating rock accompanied by crystallization of the magma (unless the magma is superheated). In particular, components derived by partial melting of KREEP—so called for its characteristic enrichment in potassium (K), rare-earth elements (REE), and phosphorus (P)—may contaminate magmas as they rise through the lunar crust or upper mantle (Binder, 1982a). Also, the mineralogy and inferred crystallization of lunar highland rocks composing the magnesium-rich suite (see below) seem to require that the magmas from which these rocks crystallized assimilated plagioclase feldspar from the crust. Finally, data on volcanic glasses suggest that magmas generated within the Moon reacted with titanium-rich cumulates to produce hybrid magmas (Delano, 1986).

In summary, lunar research has aided recent advances in our understanding of the effects, plausibilities, and complexities of petrologic processes. Our understanding of lunar igneous history has, in turn, benefited greatly from improved knowledge about magmatic processes.

Early lunar differentiation: magma ocean, global melting, or magma ponds?

The idea that the fledgling Moon was surrounded by an ocean of magma 4.5 billion years ago (fig. 7) became quickly entrenched following its introduction (Wood et al., 1970). There are three main lines of evidence for postulating the former existence of such large magma body. First, the lunar highlands appear to have large concentrations of plagioclase, as indicated by sample studies and remote-sensing data. Using the difference in average elevation between the maria and highlands, and gravity data from the Lunar Orbiter spacecraft, Wood et al. (1970) proposed that the lunar crust contains an abundance of plagioclase much greater than would be expected to be produced by partial melting of rocks of bulk Moon composition. Second, the complementary patterns of europium concentrations (normalized to chondrites) of mare basalts and highland anorthositic rocks indicate early and extensive removal of divalent europium (compatible with calcium in plagioclase) from the mare basalt source regions. The absence in returned samples of mafic cumulates complementary to anorthosites implies that these cumulates occur deep within the Moon, suggesting a very large magma system. Finally, initial $^{87}Sr/^{86}Sr$ ratios for ferroan anorthosite rocks are very primitive, suggesting

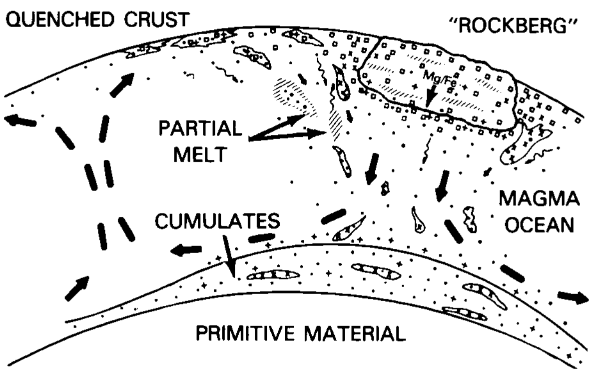


Figure 7. Schematic diagram showing the possible nature of the lunar magma ocean. Floating "rockbergs" of plagioclase-rich cumulates eventually coalesced into primordial ferroan anorthosite crust. From Longhi (1978).

that crustal formation occurred soon after lunar accretion.

Debate regarding the magma ocean centered around its original depth (estimates ranged from about 200 km to complete Moon melting) and around which of the identified lunar highland rock types formed in it [opinions ranged from only the ferroan anorthosites (fig. 8) to every rock found in the highlands!]. Such models are simple compared with the more complex picture now perceived. Some investigators have questioned whether the magma ocean initially had a composition that was the same as the bulk silicate portion of the Moon, or whether the ocean may have been a partial melt (Longhi, 1981; Shirley, 1983). Others have questioned the very existence of the magma ocean (Walker, 1983b), attributing the anorthosites that have been found to the formation of plagioclase cumulates in numerous small intrusions throughout a primordial crust. Although models lacking a magma ocean are invoked by a minority of workers, the debate has led to a needed reassessment of the origin of the lunar crust. Research into the nature of the magma ocean continues, fostered by improved knowledge of petrologic processes. For a concise summary of the current status of magma oceanography, see Warren (1985).

The reality of a lunar magma ocean perhaps depends on the total composition of the Moon's crust. Specifically, the proof or disproof of the magma ocean's existence, and the evidence for its depth if it did exist, require accurate knowledge of the crustal abundance of plagioclase feldspar and of incompatible elements such as the rare earths. We do not know with certainty how much plagioclase is in the crust or how its abundance varies vertically or laterally; the same uncertainties apply to the abundance of incompatible elements. Remote-sensing observations of the Moon are providing more information on how the lunar crust varies in composition laterally and with depth (e.g., data on the central peaks of craters and on the composition of basin ejecta). Improved understanding of basin formation and the distribution of ejecta around basins is also contributing to interpretations. More geologic studies are needed if we are to comprehend better the way in which giant impacts have garbled the record of lunar crustal formation. Ultimately, a detailed global survey of the Moon must be made from a spacecraft in polar orbit.

Primary highland rock types

Most of the samples collected in the lunar highlands are breccias formed by impacts. These are complex mixtures of preexisting rocks, many of which were themselves impact breccias. One of the most important advances in unraveling the igneous history of the lunar highlands was the development of criteria to distinguish igneous rocks, produced by crystallization of internally generated melts (fig. 9), from those produced by impact mixing. Previously, highland rocks had been lumped together as one suite, dubbed ANT, for Anorthosite, Norite, and Troctolite. Most rocks termed ANT are impact breccias, not chemically unmixed igneous rocks. Careful work showed that these "pristine" rocks (igneous cumulates) fall into two main groups: the ferroan anorthosite suite (fig. 8) and the magnesium-rich suite (composed mostly of norites and troctolites; fig. 9).

The attempt to relate the rocks of both suites to the putative magma ocean took considerable energy and creativity. Although these efforts produced interesting papers regarding potentially important processes operating in such a huge

Figure 8. Photomicrograph of the "Genesis rock," ferroan anorthosite 15415,19. This rock consists of >95% plagioclase (gray) and minor high-calcium pyroxene (yellow); as with almost all lunar anorthosites, this rock has had a complex history of shock and thermal metamorphism. Lunar ferroan anorthosites are probably remnants of the earliest lunar crust. Crossed polarizers; field of view, 2.7 mm.

magma body (Longhi and Boudreau, 1979; Longhi, 1980), there is now nearly unanimous agreement that ferroan anorthosites and magnesium-rich suite rocks are not closely related. Furthermore, our perception of the magnesium-rich suite itself has become much more complicated due to the identification of unrelated subgroups, including some subgroups richer in high-calcium pyroxene. Addition of rock types to the roster of highland pristine rocks continues each year as investigators extract clasts from breccias. Also, the chemical compositions of some impact melts and breccias show clearly that unsampled rock types must be components in them. We have not identified all types of rocks making up the lunar highlands, and the members missing from the roster might be major rock types.

Further study of lunar samples will increase our knowledge of the types and proportions of rocks in the lunar highlands. A context for them from geologic and remote-sensing studies is essential. Such investigations provide data on the distribution of known rock types and on the degree to which immense impacts have mixed materials and flung them across the Moon's surface. More detailed data from both a polar orbiter and sample returns would greatly expand our knowledge of this fundamental part of the Moon.

KREEP: as important as it is enigmatic

Nonmare samples collected from the Oceanus Procellarum region of the Moon (Apollos 12 and 14) are characterized by enrichments in incompatible elements, including potassium (K), the rare-earth elements (REE), and

phosphorus (P). Nearly all of these samples are impact-melt rocks and impact breccias; only a few are igneous rocks crystallized from internally generated melts. These incompatible-element-enriched rocks have a range of major-element compositions, but their trace elements always have the same relative abundances; for example, the lanthanum/lutetium ratio normalized to chondrites is always 2.2. These characteristics indicate that the incompatible elements are present in the rocks in the form of a cryptic component of unchanging composition. This component is termed KREEP (for its enrichment in K, REE, and P); its trace-element abundances (relative to chrondrites) are well defined, but its relative and absolute abundances of major elements remain poorly known.

Figure 9. Photomicrograph of spinel troctolite clast in lunar breccia 67435,14. In this pristine lunar igneous cumulate, the original texture is largely preserved; subhedral and euhedral olivine crystals (gray) are poikiliticly enclosed by plagioclase (white). Plane light; field of view, 2 mm. (Photograph by Graham Ryder, Lunar and Planetary Institute.)

The regional distribution of KREEP on the Moon is highly asymmetric (fig.10). Enhancements of thorium concentration (indicative of KREEP) occur in the Fra Mauro, Archimedes, and Aristarchus areas of the Imbrium-Procellarum region of the Moon (Metzger et al., 1977); thorium contents in these regions are enriched by factors of 10 or more over the average global surface concentration (1.3 ppm). Additional areas rich in KREEP include the Balmer and Marginis Basins on the east limb and the Van de Graaf-Ingenii region of the far side. The cause of this asymmetric distribution of KREEP is unclear; extrusion of ancient KREEP volcanics, excavation by impact basins, and lateral crustal variations in KREEP concentrations have all been proposed.

KREEP has been mixed with other highland rocks by impacts to form KREEP-rich breccias. The oldest of these breccias have ages of about 3.9 billion years, indicating that KREEP predates this time. Isotopic systematics for KREEP samples strongly indicate its formation by 4.35 billion years ago (Carlson and Lugmair, 1979). One potentially important constraint on the history of KREEP has been generally overlooked; small, feldspathic granulitic breccias have been collected from every lunar landing site, including those whose materials are rich in KREEP. These granulitic breccias were formed by impact mixing of upper crustal materials, appear to be 4.2 to 4.1 billion years old, and have virtually no KREEP component. These properties suggest that KREEP was not present on or near the surface of the Moon prior to about 4 billion years ago (Warner et al., 1977). Whether this constraint suggests a volcanic extrusion mechanism for KREEP (Shirley and Wasson, 1981) or an origin by basin excavation (Taylor, 1982) is not clear.

The current consensus is that KREEP probably represents the last crystallization product of the magma ocean (Warren and Wasson, 1979; Binder, 1982a). There is growing evidence that

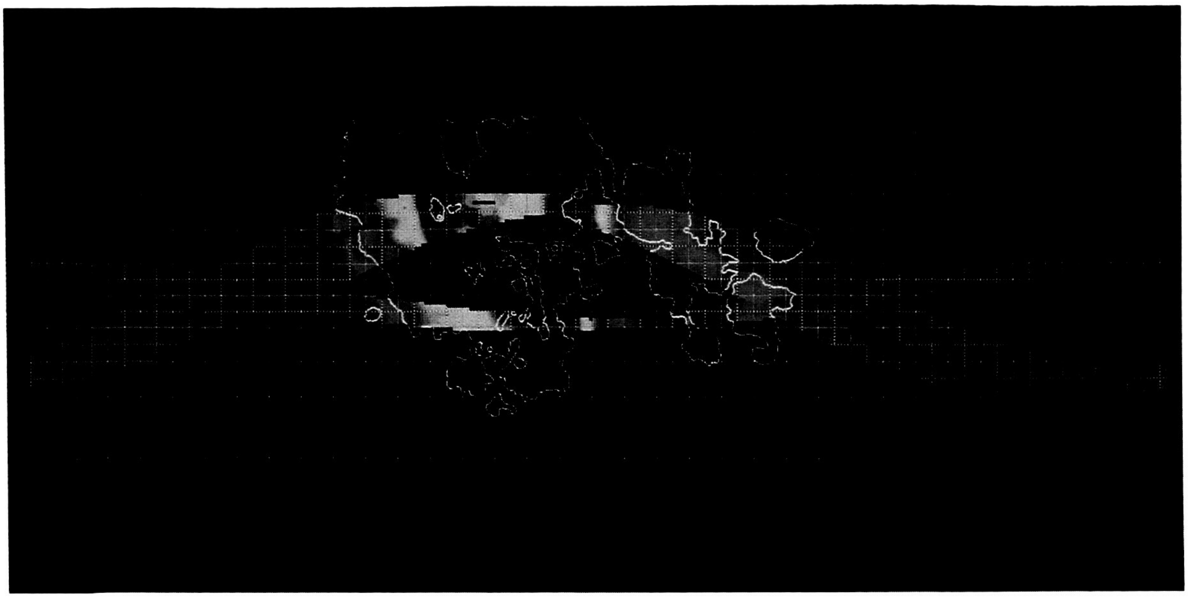


Figure 10. Map of thorium concentration on the Moon derived from data obtained by orbiting Apollo 15 and 16 gamma-ray spectrometers. Colors correspond to thorium concentration (in ppm): violet, < 0.9; purple, 0.9 to 1.9; blue, 1.9 to 2.8; green, 2.8 to 3.8; yellow, 3.8 to 4.7; orange, 4.7 to 5.7; red, > 5.7. Thorium content is indicative of KREEP; thus, this map shows that the regional distribution of KREEP on the Moon is highly asymmetric, with major concentrations in the Imbrium-Procellarum region. Data from Metzger et al. (1977).

KREEP contaminated many (perhaps most) magmas as they oozed toward the lunar surface from their sources in the lower crust or mantle. Binder (1982a) has emphasized the role of KREEP assimilation in mare-basalt genesis, and Warren and Wasson (1980) proposed KREEP assimilation for magnesium-rich suite magmas. Recent work on aluminous mare basalts extracted from Apollo 14 breccias has demonstrated dramatically the role of KREEP assimilation (Dickinson et al., 1985; Shervais et al., 1985). Some of these basalts have major-element abundances like those of mare basalts, yet have KREEP trace-element patterns.

Lunar Tectonics

The relatively simple tectonic evolution of the Moon as compared with Mars or Ganymede does not lessen its importance. Both Mercury and Mars show an early period of crater- and basin-controlled tectonism resembling that of the Moon; therefore, contrasts in tectonic styles are important for comparative planetology. Studies in lunar tectonics during the last decade have evolved from detailed studies of individual structural features to models attempting to place such features in global or regional context.

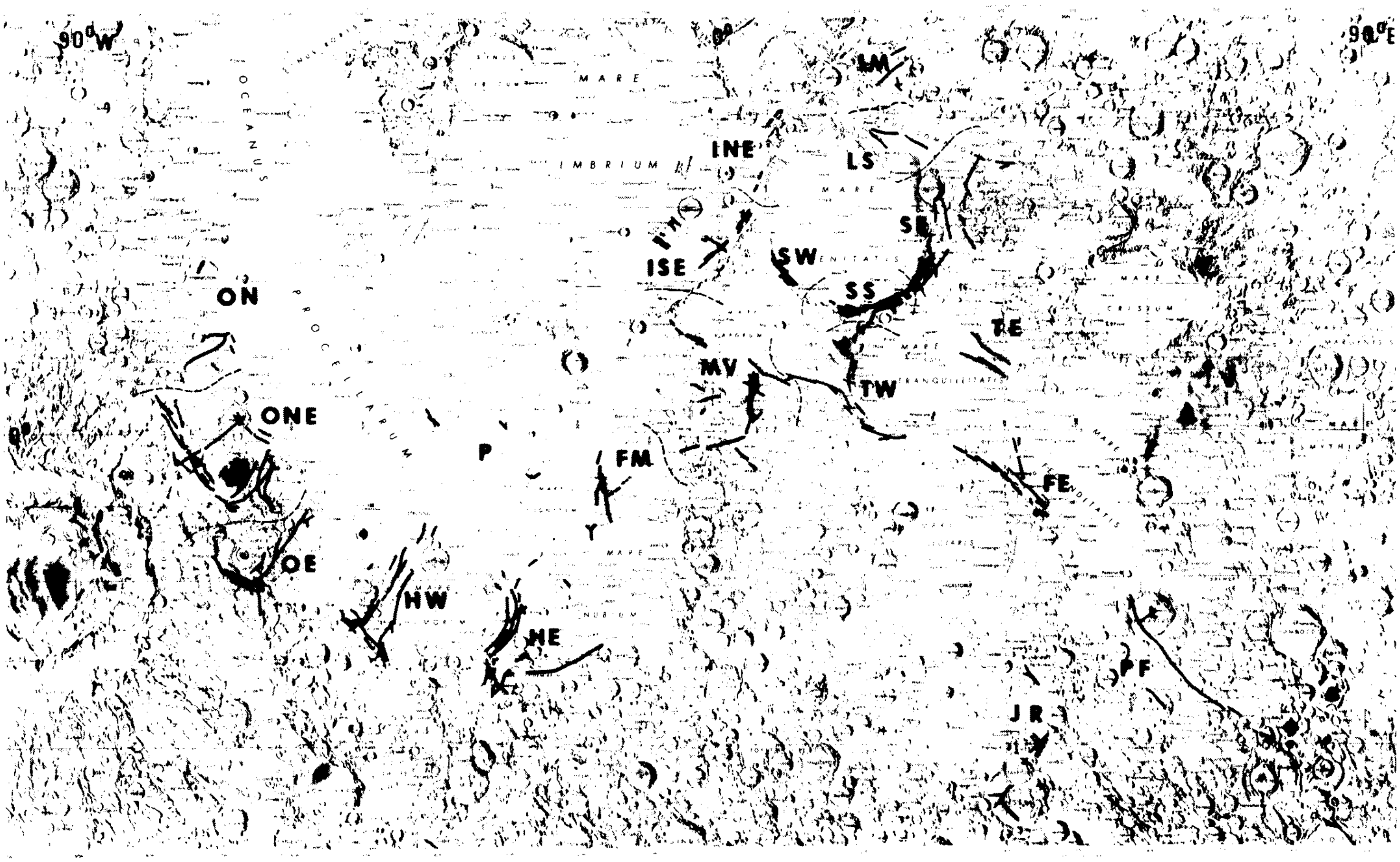
Three features dominate broad-scale lunar tectonic expression: wrinkle ridges, grabens, and scarps. Wrinkle ridges were once widely viewed as unique to the maria; thus hypotheses for their origin were intimately related to mare basalt emplacement. Some early studies suggested an origin directly related to the cooling basalts (e.g., squeeze-ups of lava), but evidence for a structural origin for most wrinkle ridges has been discovered in mapping (Muehlberger, 1974), morphology (Lucchitta, 1976; Schultz, 1976a), and Apollo radar sounder studies (Maxwell and Phillips, 1978; Sharpton and Head, 1982). The identification of wrinkle ridges extending into and across the cratered highlands (Luccitta, 1976; Schultz, 1976a; Binder, 1982b) dissociates them from a specific geologic formation. The complex associations and differences in appearance of wrinkle ridges may require an assortment of origins, including primarily surfical, near-surface thrust

faults related to vertical movement at depth (Lucchitta, 1976) and deep-seated thrust faulting (Baldwin, 1963; Solomon and Head, 1979; Sharpton and Head, 1982).

Grabenlike lunar rilles were also recognized before Apollo, but later detailed studies established their time of formation (fig. 11; Lucchitta and Watkins, 1978) and distribution (Guest and Murray, 1976; Solomon and Head, 1980). Because most grabens are older than about 3.6 billion years, and most wrinkle ridges continued to form after 3.0 billion years ago, Solomon and Head (1979) proposed that graben formation was related to a change in the global stress field superposed on mascon-loaded basins. The change in the global stress field from an early epoch of expansion to a long period of compression was linked to a change in the global thermal history. The entire story may be even more complex. The identification of very young scarps in the highlands (Schultz, 1976a; Masursky et al., 1978; Binder, 1982b) may indicate continued global contraction.

The role of impacts in the distribution and origin of lunar tectonic patterns has been documented, but with contrasting interpretations. Topographic data provided by Apollo photogrammetry confirmed earlier impressions

Figure 11a. Map of the distribution of graben systems on the lunar near side. Letters indicate the names of graben clusters, as follows: ON, Orientale north; ONE, Orientale northest; OE, Orientale east; HW, Humorum west; HE, Humorum east; P, Procellarum; FM, Fra Mauro; INE, Imbrium northeast, ISE, Imbrium southeast; LM, Lacus Mortis; LS, Lacus Somniorum; SW Serenitatis west; SS, Serenitatis south; SE, Serenitatis east; MV, Mare Vaporum, TW, Tranquillitatis west; TE, Tranquillitatis east; FE, Fecunditatis; PF, Petavius, Furnerius; JR, Janssen-Reichenbach. From Luchitta and Watkins (1978).



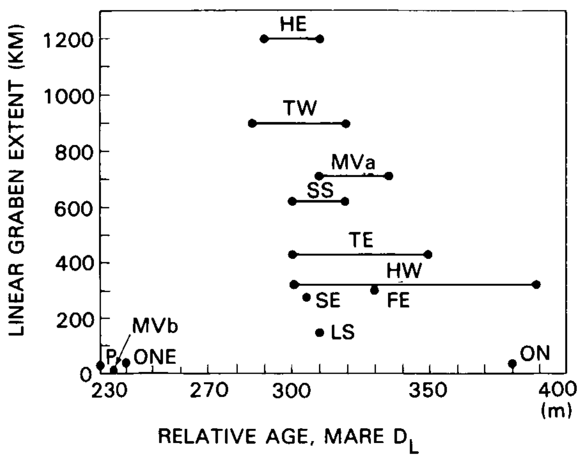


Figure 11b. Graben systems (fig. 11a) plotted as a function of linear extent of grabens and range in relative age of maria on which grabens are superposed. Grabens are found mostly on maria older than about 3.6 billion years. From Lucchitta and Watkins (1978).

that many lunar impact craters localized subsequent volcanic/tectonic activity, resulting in floor uplift and failure (Schultz, 1976b). Such craters may have localized sill-like intrusions beneath crater floors. Hall et al. (1981) suggested, however, that some of these craters may have relaxed by viscous flow of the crust. At much broader scales, Mason et al. (1976) noted the strong structural influence of the Imbrium Basin on the distribution of grabens. Whitaker (1981) and Wilhelms (in press) argued that the distribution of ridges delineates an ancient nearside megabasin, whereas Schultz and Spudis (1985) related many of the same ridges and grabens to a pattern radial and concentric to the Imbrium Basin.

Crustal Structure

Geophysical constraints

Our knowledge of lunar crustal density, composition, and thickness is constrained primarily through the interpretation of seismic, gravitational, and topographic data. Seismic constraints on crustal thickness and composition are limited mainly to the Mare Cognitum region near the Apollo 12 and 14 landing sites, where the construction of detailed crustal seismic velocity models was possible (Toksoz et al., 1974). A crustal thickness of 55 to 60 km at this location was inferred, but the existence of rocks ranging from gabbro to anorthosite is consistent with the velocity limits obtained from these models (Liebermann and Ringwood, 1976). Goins et al. (1981a) inferred a thickness of 75 ± 5 km beneath the Apollo 16 Descartes highlands site on the basis of apparent reflected phases from the transition zone between the crust and mantle. The greater thickness here than in the Mare Cognitum region would be sufficient to compensate isostatically the 1.5-km greater elevation of the Apollo 16 site.

The observed gravity field of the Moon is of low contrast, reflecting near-isotatic compensation of surface topography, and it is dominated by the mascon anomalies of some impact basins (fig. 12; Muller and Sjogren, 1968; Solomon and Head, 1980). Analyses of Bouguer gravity anomalies show that isostatic compensation is nearly complete for pre-Imbrian highland topography but incomplete for certain Imbrian-age structures such as the Apennine Mountains and the mascons, indicating global cooling and thickening of the elastic lithosphere since about 4 billion years ago.

In principle, isostatic compensation of the lunar highlands may be effected either by lateral thickness variations in a crust of nearly constant density (Airy isostasy) or by lateral density variations in a crust of nearly constant thickness (Pratt isostasy). Analyses of orbital geochemical data have produced little evidence for lateral crustal density variations that correlate with topography over most of the Moon (Haines and Metzger, 1980). These results, combined with the greater crustal thickness beneath the Apollo 16 highlands site, favor dominantly Airy compensation. However, more seismic thickness determinations at other locations are needed for confirmation. Assuming an Airy compensation model, Bills and Ferrari (1977) used available gravity and topography data to show that the average crustal thickness is greater on the far side than the near side (see also Wood, 1973) and that crustal thickness ranges from 30 to 35 km beneath the mascons to 90 to 110 km beneath the highlands, with a mean of about 70 km. Such a thickness asymmetry would be sufficient to explain the

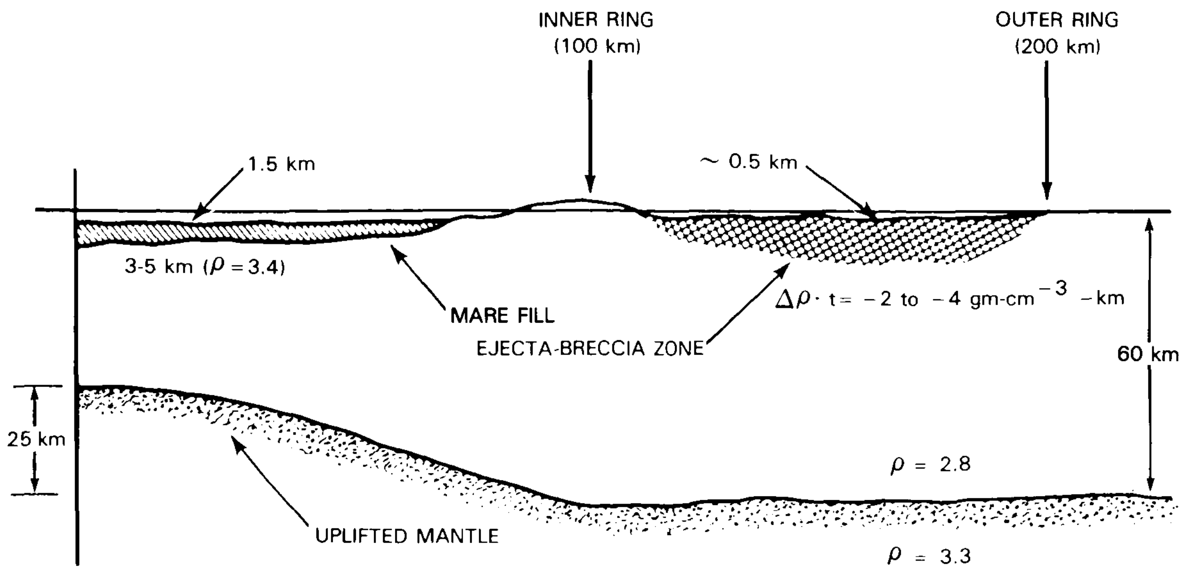


Figure 12. Schematic cross-section of lunar Grimaldi Basin determined from gravity data. The uplift of the mantle material near the basin center is at least partly responsible for the observed positive gravity anomaly (mascon) in the basin. From Phillips and Dvorak (1981).

observed center-of-figure to center-of-mass offset of 2.0 to 2.5 km (Kaula et al., 1974) and may also explain the dominance of maria on the near side by preferential basalt flooding of thin-crusted, low-lying regions (fig. 13).

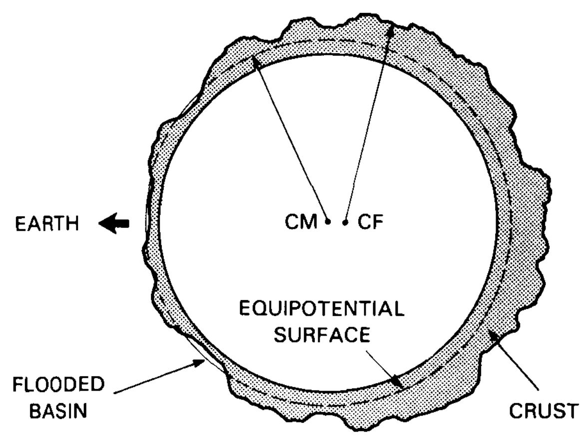


Figure 13. Schematic cross-section through the Moon showing displacement of center of mass (CM) toward Earth relative to center of figure (CF). Crustal thickness and surface relief are greatly exaggerated. From Taylor (1982).

Vertical stratification of the lunar crust?

Whether the lunar crust is vertically uniform or layered is important for determining lunar sample provenance and crustal petrogenesis. Models based on initial Apollo sample results suggested a crust tens of kilometers thick with a bulk composition of anorthosite (Wood et al., 1970). Further sample data, geophysical information on crustal thickness, and geologic data on basin settings led to a suggestion that the lunar crust becomes more mafic with depth (Charette et al., 1977; Ryder and Wood, 1977). An important source of information on this problem is the composition of multiring basin ejecta, which are derived from depths of many kilometers in the crust. Spudis et al. (1984) noted a positive correlation between the fraction of norite in basin ejecta and the size of the basin, normalized to local crustal thickness. This can be interpreted to mean that the lower crust has a bulk composition of norite, whereas the upper crust is more anorthositic (fig. 14). However, the solution to the problem of vertical crustal layering requires more

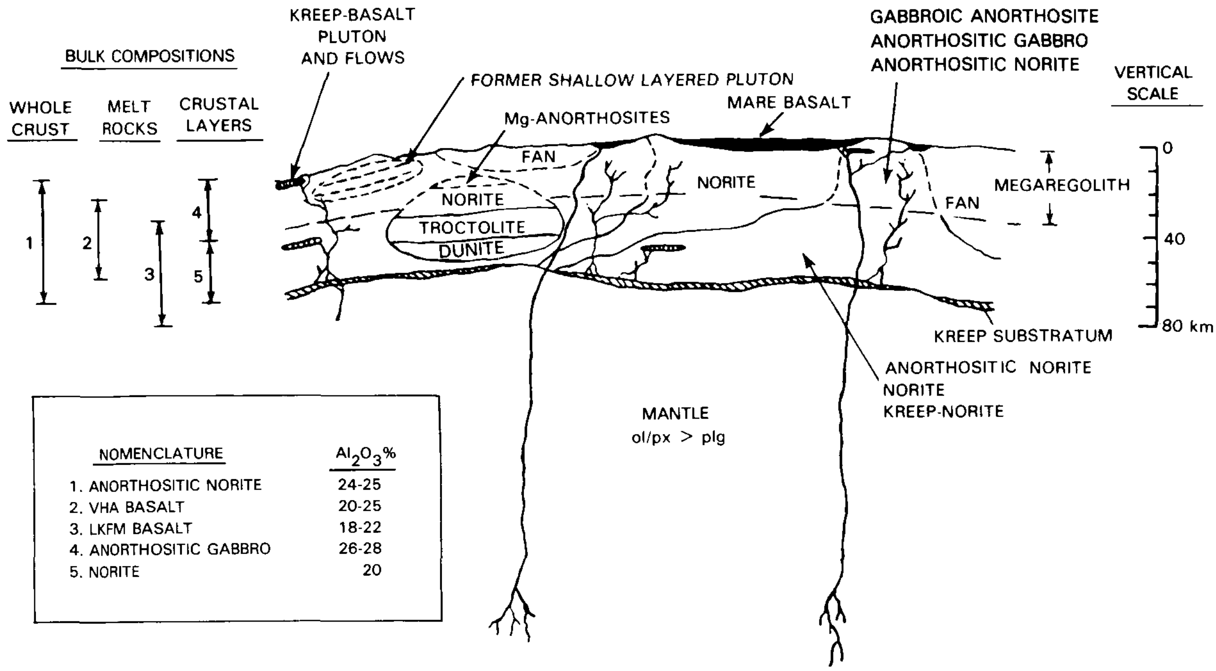


Figure 14. Schematic cross-section of the lunar crust showing possible geologic relations among lunar rock types. The provenance of bulk compositions is shown at the left. This reconstruction is one of several possible interpretations of a wide variety of lunar sample, remote-sensing, cratering, and geophysical data. FAN, ferroan anorthosite; VHA, very high alumina basalt; LKFM, low K Fra Mauro basalt; ol/px > plg, olivine and pyroxene greater than plagioclase.

data for many basins distributed over the Moon and probably will not be found until global data are available from the Lunar Geoscience Observer (LGO).

MANTLE

Geophysical Data

Because the lunar mantle dominates the mass of the Moon, models of bulk Moon composition are necessarily tied to evaluations of mantle composition and structure. In addition, the depth of differentiation of the early Moon may be deduced in principle from limits on composition as a function of depth in the lunar mantle.

Geophysical constraints on the lunar mantle are determined primarily by the interpretation of seismic velocity models. In the upper mantle (depths of <400 to 500 km), P- and S-wave velocities are relatively well determined and imply an Mg/(Mg + Fe) ratio for mantle olivines and pyroxenes in the range of 0.70 to 0.85 (Nakamura et al., 1974). Such a range is in agreement with independent estimates for mare basalt source regions at comparable depths (Ringwood and Essene, 1970; Ringwood, 1979). In the middle mantle (500 to 1000 km in depth), the most recent analysis of the complete Apollo arrival time data set (Nakamura, 1983) has yielded mean velocities with rather large one-standard-deviation limits (i.e., the probability that actual velocities are within the derived range, assuming random errors, is only about 68%). An apparent velocity increase at these depths (fig. 15) implies either a large garnet fraction (garnet is a stable aluminum-bearing phase at these depths) or an increase in the Mg/(Mg + Fe) ratio for mafic silicates (see Hood (1986) for a more complete discussion). Mantle compositions consistent with Nakamura's (1983) seismic velocity limits are currently being modeled by several groups. For depths of >1000

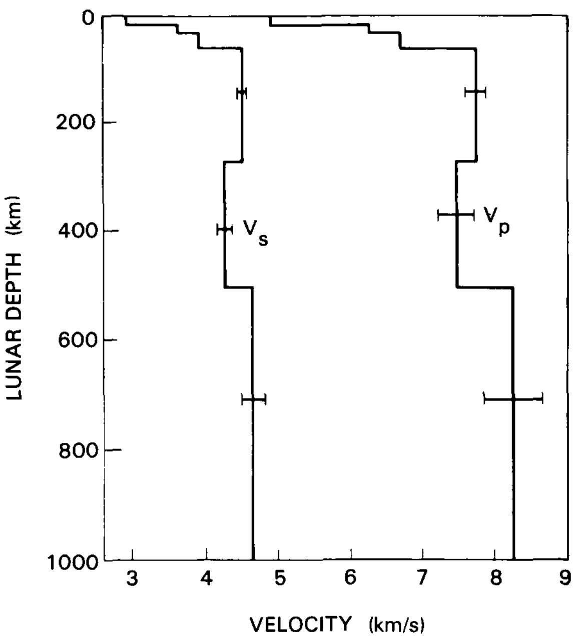


Figure 15. Seismic velocity structure of the lunar interior as derived from the complete Apollo arrival time data set. V_s and V_p refer to seismic shear wave and longitudinal wave velocities, respectively. From Nakamura (1983).

km, virtually no seismic velocity limits or compositional constraints are available.

Volcanic Samples and Their Source Regions

There is unanimous agreement among petrologists and geochemists that basalts are produced by partial melting inside planets. Therefore, basalts are records of the Moon's interior and reveal information about inaccessible areas of the Moon. This information, however, has been garbled by the myriad of igneous processes that have modified magma compositions as they migrated from their source areas to the Moon's surface. The important roles of these processes were not fully appreciated until several years ago. Consequently, models of the origin of mare basalts, and hence of the lunar interior, were oversimplified. Nevertheless, it still seems correct that the mare basalt source regions in the lunar mantle formed during the initial lunar differentiation, probably as cumulates from a magma ocean; see the Basaltic Volcanism Study Project (1981) and Taylor (1982) for reviews of models for the origin of mare basalts.

Not all magmas were greatly altered before eruption, however. There are deposits of pyroclastic glasses, such as Apollo 17 orange glass (fig. 16; Heiken et al., 1974), which may have ascended rapidly from their source regions in the mantle (Delano, 1979, 1980). These deposits appear to cover areas of both lunar maria and terrae (fig. 17), and more work is needed to determine deposit compositions in detail. One critical fact about pyroclastic glass deposits is that they are enriched in volatile elements such as sulfur, chlorine, zinc, silver, and gold (see Delano (1986) for a review of volatile contents in volcanic glass). These potentially useful substances occur on the surfaces of individual glass beads. The origin of these volatiles is obscure, but their presence suggests that pockets of volatile-rich rocks existed in the lunar interior. Mapping the global distribution of pyroclastic, dark-mantling materials is a major task for an LGO mission.

CORE

The Moon's mean density indicates that it must be severely depleted in iron in comparison with other terrestrial bodies; therefore, a metallic core must be small or nonexistent. This property has been considered a fundamental constraint on lunar origin, suggesting, for instance, either selective accretion of iron-poor planetesimals under the influence of the nearby Earth or formation mainly from terrestrial mantle material.

A determination of the existence and actual radius of a lunar metallic core is important for several reasons. This information is needed to allow valid interpretation of a series of global geophysical measurements, including the moment-of-inertia, crustal-paleomagnetism, and laser-ranging data (see below). Also, a determination of the core mass will help to distinguish among models of lunar origin. We need to know the amount of segregated metal in the Moon to calculate the original lunar siderophile element abundances; this information can be used to decide whether the Moon formed from undifferentiated solar nebula material (binary accretion

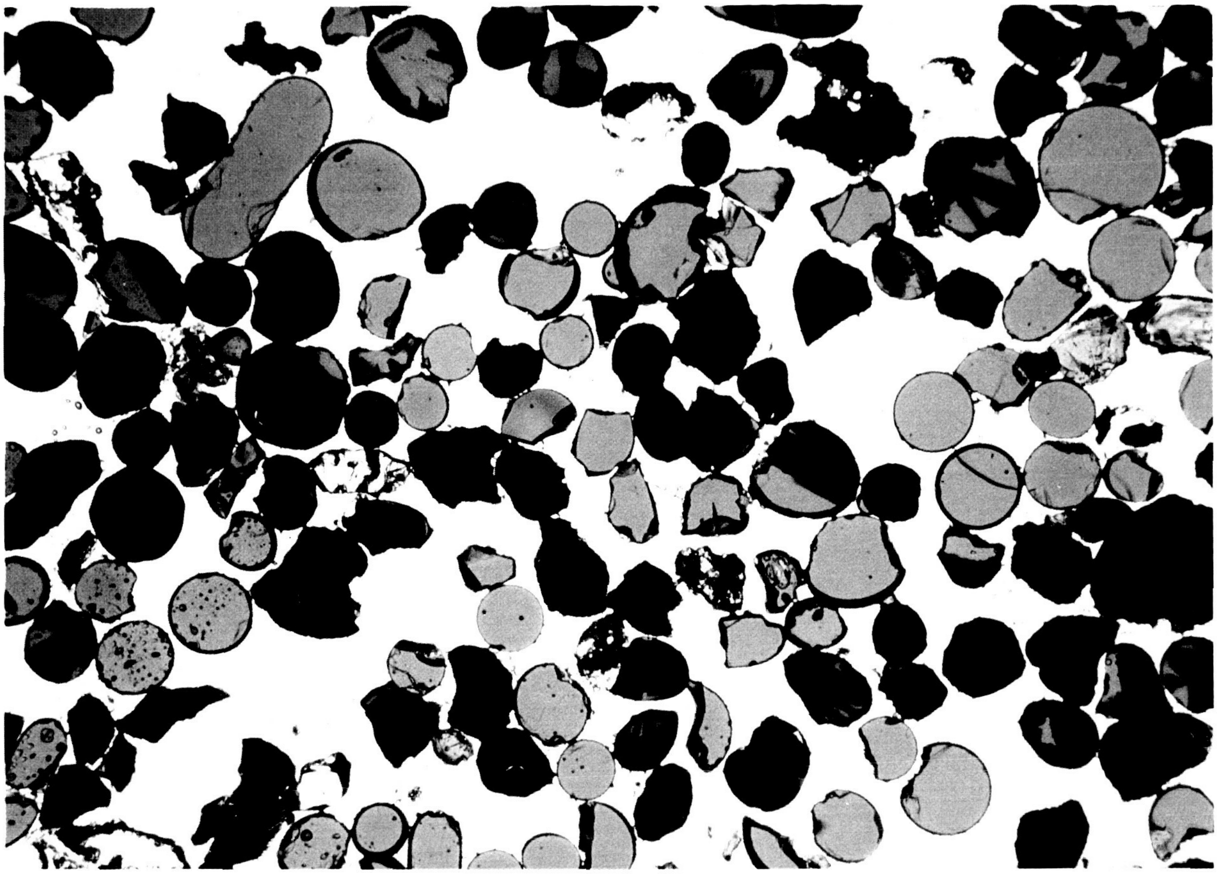


Figure 16. Photomicrograph of Apollo 17 orange soil 74220,335. Orange spheres are volcanic pyroclastics that erupted during lunar fire-fountaining. Samples such as this may represent primary (unfractionated) magmas from the deep interior of the Moon. Plane light; field of view, 2.5 mm. (Photograph by Graham Ryder, Lunar and Planetary Institute.)

hypothesis) or from differentiated material such as that of Earth's mantle (impact "fission" hypothesis; Newsom (1984) and references therein).

Geophysical constraints on the existence and radius of a metallic lunar core are suggestive but not definitive. An early interpretation of the arrival of a single seismic P-wave from a far-side meteoroid impact was consistent with the existence of an iron-rich core with a radius of 170 to 360 km (Nakamura et al., 1974). However, in a later evaluation of the uncertainties in this result, no reliable seismic evidence was found for or against a metallic core with a radius less than about 500 km (Goins et al., 1981b; Nakamura et al., 1982). Limits on electrical conductivity in the Moon, derived from electromagnetic sounding data, provide an alternative but equally difficult means of constraining the radius of a metallic core (fig. 18). Methods that analyze measurements of time-varying magnetic fields to deduce limits on electrical conductivity as a function of depth have obtained only an upper limit (in the range of 400 to 500 km) on the radius of a highly conducting metallic core (see the review by Hood, 1986). Methods that measure the induced lunar dipole moment—using magnetometer data for times when the Moon was in the quasi-vacuum environment of the geomagnetic tail—have resulted in possible evidence for a highly conducting core with a radius of $>$400 km (Russell et al., 1981). An additional line of evidence for a central fluid core in the Moon has been derived from laser ranging measurements of physical libration parameters, indicating a larger dissipation of rotational energy in the Moon than would be expected in the absence of a fluid core. For particular laminar and turbulent core-mantle coupl-

ing models, Yoder (1981) has applied the physical libration data to obtain a rough estimate of 330 km for the radius of such a core. However, the core density, and hence composition, cannot be determined from such models, so that a molten silicate core cannot be excluded as an alternative explanation. Other geophysical measurements relevant to the question of the existence of a core include the moment-of-inertia and lunar paleomagnetic data, but these measurements are also not definitive. (They are discussed below under Global Properties.)

In summary, several geophysical observations suggest, but do not prove, the existence of a lunar metallic core whose radius is in the range of 330 to 450 km. If we assume a dominantly iron composition, such a core would represent 2 to 4% of the lunar mass. For comparison, Newsom (1984) has estimated that if the Moon formed entirely from terrestrial mantle material (which is already depleted in siderophile elements relative to chondritic meteorites), then segregation of only 0.1 to 1% metal would be required to produce the present estimated lunar siderophile-element abundances. The corresponding radius of a dominantly iron core would be <285 km. Consequently, the geophysical evidence suggests a possible core radius that is somewhat larger than expected if the Moon formed entirely from material of Earth's mantle. However, additions of metal to a protomoon composed largely of terrestrial mantle material by differentiated circumterrestrial planetesimals or by a large terrestrial impactor would circumvent this difficulty. This discussion illustrates the eventual constraints on models of lunar origin that will accrue when more definitive evidence for the existence and mass of a lunar metallic core has been obtained. The preferred approach for establishing the radius of a metallic core, as well as the structure and composition of the mantle, is seismology supplemented by electromagnetic sounding; such sounding would use a more widely distributed network of surface instruments than was provided by Apollo. Further independent measurements of the lunar-induced magnetic dipole moment by a polar-orbiting satellite (LGO) would

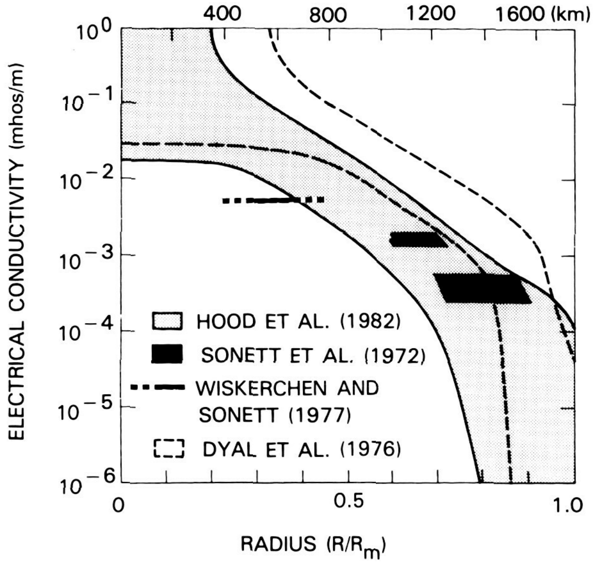
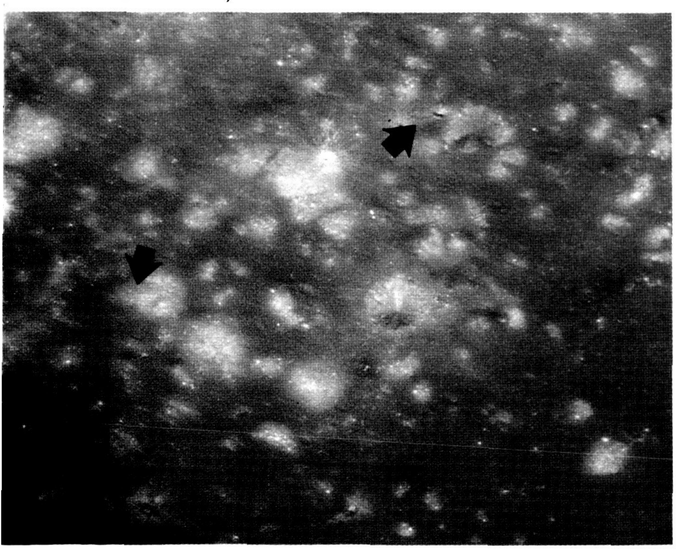


Figure 18. Summary of electrical conductivity estimates of the lunar interior based on analyses of simultaneous Apollo 12 and Explorer 35 magnetometer data. R_m is the mean lunar radius (1738 km). One conclusion of these studies is that a highly conducting lunar metallic core cannot be larger than 400 to 500 km in radius.

Figure 17. Orbital view of Sulpicius Gallus Formation, a dark-mantling deposit of probable pyroclastic origin. Small impact craters (arrows) have excavated orange material, which may correlate with orange pyroclastic glasses collected at the Apollo 17 landing site. North at right; field of view about 20 km. (NASA photo AS17-22771)



also be helpful in determining limits on the core radius and would probably predate establishment of a surface network.

GLOBAL PROPERTIES

Moment of Inertia

The lunar mean density has been known with reasonable precision for many decades, but accurate determination of the moment of inertia required a relatively precise evaluation of low-degree gravity harmonic coefficients, which was not achieved until the mid-1970s. Initial evaluations of the relevant coefficients, C_{20} and C_{22}, based on relatively low-altitude orbiter tracking data were not accurate because of limited data coverage and the effects of truncating spherical harmonics of gravitational potential. As a result, it was not clear that the lunar dimensionless moment of inertia was significantly different from that of a uniform density sphere (0.40). More accurate values for these coefficients were obtained from later analyses of long-term variations of periapsis and node for the high-orbiting Explorer 35 and 49 spacecraft that yielded a moment of inertia value of 0.391 ± 0.002 (Blackshear and Gapcynski, 1977). A further combined analysis of laser ranging data and Doppler tracking data from the Lunar Orbiter 4 spacecraft, which also had a relatively high-altitude orbit, yielded a value of 0.3905 ± 0.0023. The consistency of these two results from optimally selected data sets makes it probable that the true lunar moment of inertia lies within the error limits of these two determinations.

Although the lunar moment of inertia is now known to be slightly less than that of a uniform sphere, implying some form of density increase with depth, the density increase cannot be determined uniquely. In particular, in the absence of other information, models with or without dense metallic cores are equally plausible. Constraints on mantle density changes, in addition to data on crustal mean density and thickness, are needed if the moment of inertia is to be a significant constraint on density models for the deep interior. Because hydrostatic compression is largely offset by thermal expansion in the Moon, the most important cause of radial density variations is radial changes in composition or mineralogic phase. These radial changes in composition are limited geophysically almost entirely by the interpretation of seismic velocity models. This conclusion reinforces the need for more complete analysis and interpretation of lunar seismic velocities and for the eventual collection of new seismic data from the Moon.

Heat Flow

Heat-flow-probe measurements were successfully obtained only at the landing sites of Apollos 15 and 17. Initially reported values were overestimated by 30 to 50%, leading to similarly overestimated model values of bulk lunar uranium and thorium abundances. Later, more accurate estimates of bulk thermal properties for regolith material led to final heat flow estimates of 21 and 16 mW/m^2 at the Apollo 15 and 17 sites, respectively (Langseth et al., 1976). These authors extrapolated the observed values to calculate an approximate global average using orbital gamma-ray measurements of surface thorium abundances and inferred crustal thicknesses. Conel and Morton (1975) and Rasmussen and Warren (1985) have suggested that because the Apollo 15 and 17 sites were near the edges of maria, where the megaregolith is likely to be thin, estimates of thermal conductivities and the corresponding heat flows for the whole Moon are likely to be anomalously high. Correcting for the effect of locally thin megaregolith, they derived substantially lower global heat flow averages. Considering the uncertainties in present global heat flow estimates and the assumptions involved in converting these estimates to bulk uranium and throium abundances, it is unclear that these data provide incontrovertible evidence for a lunar enrichment in refractory lithophile elements relative to chondritic meteorites or Earth's mantle.

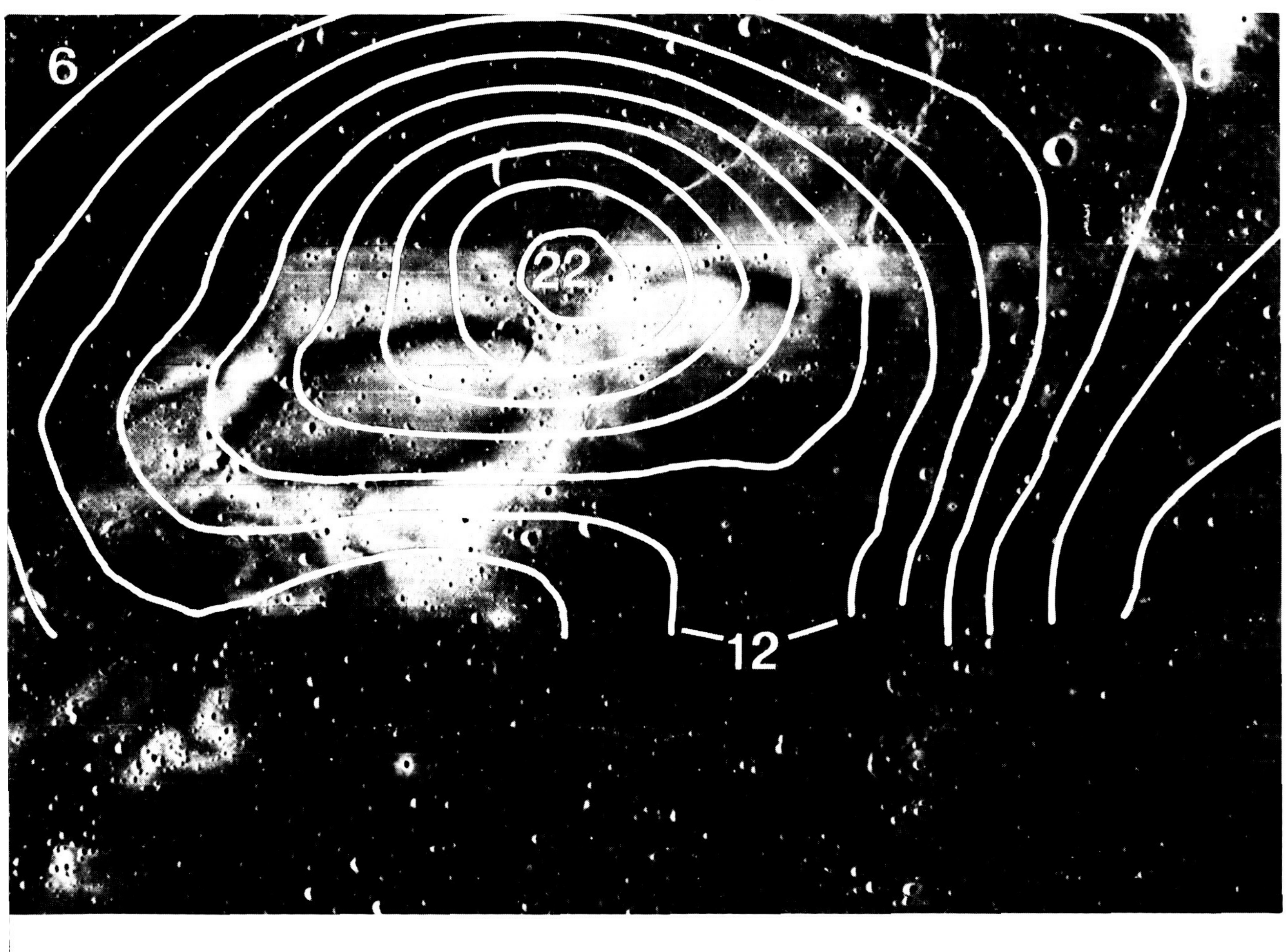
Paleomagnetism

Before the Apollo missions, the Moon was regarded as magnetically inert because previous flybys and orbiters had detected no intrinsic lunar magnetic field and because its low mean density required a small or negligible metallic core. Sur-

prisingly, both surface and orbital measurements during the Apollo missions, as well as returned sample analyses, demonstrate a pervasive magnetization of lunar crustal materials. If this magnetization is due in whole or in part to a former core dynamo, by analogy with the terrestrial case, then knowledge of the presence of a metallic core would follow, together with other possible deductions with respect to lunar internal and dynamical evolution (see the review by Runcorn, 1983).

During the past 10 years, continued analysis of Apollo orbital data and of sample paleomagnetic data has yielded new insights into the properties of the paleomagnetism, although its origin is still unresolved. Correlative studies of orbital magnetic anomalies with surface geology showed that many anomalies correlate with relatively surficial impact-produced units such as the Fra Mauro and Cayley Formations. The strongest anomalies were found to correlate with swirl-like albedo markings of the Reiner Gamma Formation (fig. 19). The geologic origin of the swirls is still not established, although some type of impact-related origin is indicated. One possibility involves deposition of secondary ejecta embedded in a transient, impact-generated magnetic field. Such a field has been predicted theoretically (Hide, 1972; Srnka, 1977; Hood and Vickery, 1984) and tentatively identified in the laboratory (Bianchi et al., 1984). Alternatively, the swirls may represent heating and scouring by the tenuous gases of a cometary coma in the presence of a compressed magnetic field associated with

Figure 19. The Reiner Gamma Formation, an unusual albedo marking (approximately 30 by 60 km in extent) in western Oceanus Procellarum that correlates with the strongest magnetic anomaly detected with Apollo subsatellite magnetometers. The origin of both magnetic anomaly and albedo markings remains unresolved. Contour lines represent total magnetic field strength in nanoteslas at subsatellite altitude (approximately 20 km).



the comet (Schultz and Srnka, 1980). Recent spectral studies (Bell and Hawke, 1983) lend support to this hypothesis, but the issue will remain unresolved until high-resolution orbital magnetic field data and spectral data can be obtained.

On the other hand, other aspects of the paleomagnetic data appear to be more consistent with steady magnetizing fields, such as would have been provided by a core dynamo. The few valid Thellier-Thellier paleointensity determinations for dated samples, together with other more approximate methods, indicate maximum lunar surface paleofields on the order of 1 gauss during the period 3.6 to 3.9 billion years ago, and much lower field intensities outside this period (Cisowski et al., 1983). These authors interpreted the inferred high-field epoch in terms of a temporary core dynamo. In addition, the stable normal remanent magnetism (NRM) component of many mare basalts has been interpreted as mainly thermoremanent in origin; that is, the primary NRM was most probably acquired by cooling through the Curie point during formation of the basalt (Fuller, 1974). In a general review of lunar paleointensity data, Collinson (1984) also favored an early core dynamo, but he discussed as well the probable importance of transient field generation mechanisms associated with impact processes for samples such as regolith breccias and glasses, which acquired their magnetizations since about 3.0 billion years ago. An important example in this category is 70019, an Apollo 17 impact-glass sample dated as < 100 million years old that yeilded a Thellier-Thellier paleointensity of 0.025 Gauss, significantly larger than observed present-day surface fields (Sugiura et al., 1979).

In addition to continued analysis of existing orbital and sample paleomagnetic data, two major classes of future data acquisition will significantly increase our ability to understand paleomagnetism and evaluate its implications for lunar history. First, global high-resolution vector measurements of lunar magnetic anomalies will lead to more definitive evidence for or against a former large-scale lunar magnetic field. Anomaly correlations with surface geology and directional properties of the magnetization can be made in much greater detail by computer-modeling studies than by the use of Apollo magnetometer data, whose high-resolution coverage was limited to less than 10% of the lunar surface. Such anomalies can be mapped by the planned LGO spacecraft if it achieves periapsis altitudes of < 50 km and if its coverage is well distributed around the Moon. Second, the return of additional samples from at least some major anomaly sources, including the Reiner Gamma swirls (table 3) as well as oriented "bedrock" samples, preferably from dated mare basalt flows, will provide a much stronger basis for interpreting both the orbital data and sample paleointensity data. In the meantime, further analyses of existing data, particularly for the purpose of establishing the nature and properties of lunar ferromagnetic carriers, are valuable. These efforts are needed not just to establish the nature of lunar paleomagnetism but also to provide a framework for understanding paleomagnetism on other solar system bodies.

Bulk Composition

Estimating the bulk composition of a planetary body is difficult. This is true even for the Moon, for which we have samples and other compositional data, because this information pertains only to the uppermost crust. Our knowledge of compositional variations within the crust is meager. We know even less about the composition and its variation in the lunar mantle. Nevertheless, geochemical principles allow several constraints to be placed on the Moon's bulk composition. This topic has been reviewed by Drake (1986) and other authors in *The Origin of the Moon* (Hartmann et al., 1986).

The Moon's bulk composition is one of the most important constraints on its origin. Specifically, how does the composition of the Moon compare with the composition of Earth's mantle? Earth's mantle and the Moon lie on the same mass fractionation line in terms of oxygen isotope composition. The Moon is depleted in siderophile elements (these partition strongly into metallic-iron phases) and in volatile elements. Compared with Earth, the Moon contains the same or perhaps slightly higher concentrations of

refractory elements (e.g., uranium, thorium, and the rare earths) that vaporize only at high temperatures; has a lower ratio of Mg/(Mg + Fe) (although some estimates of the lunar value suggest that this ratio could be the same in Earth's mantle and the Moon); and has a higher Fe/Mn ratio. The evidence from oxygen isotopes comes nearest to proving a close genetic relation between Earth and Moon, but other evidence is ambiguous.

Origin of the Moon

The three traditional hypotheses for lunar origin—fission from, capture by, and coaccretion

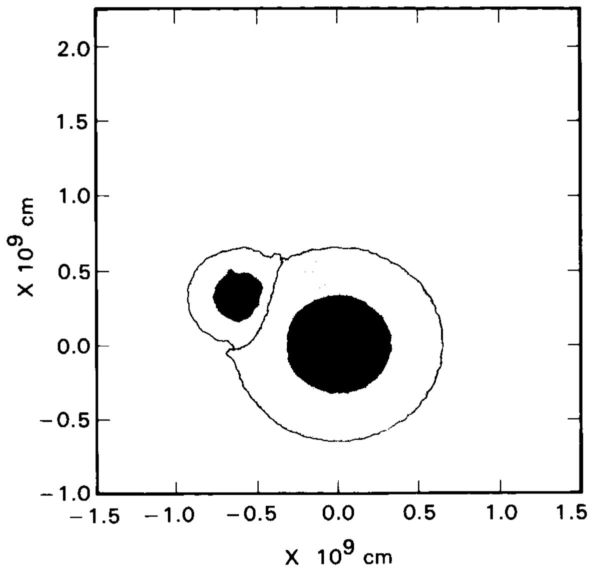
Table 3. Potential landing sites for future unmanned lunar sampling missions (after Wilhelms, 1985)

Site	Geologic unit	Landing area	Objective
1	Nectaris Basin	Ejecta near 35°S, 42°E Plains (impact melt?) near 22°S, 41°E	Absolute age Composition
2	Copernican mare	Southeast of Lichtenberg near 31°N, 67°W	Absolute age Composition of source
3	Terra plains	Albategnius Ptolemaeus	Nonmare volcanism or buried mare basalt flows?
4	Terra domelike landforms	Gruithuisen delta or gamma Hansteen alpha	Nonmare volcanism?
5	Far-side mare	Floor of Tsiolkovsky Mare Ingenii	Absolute age Composition of source
6	Maunder Formation (Orientale Basin impact melt)	South of Mare Orientale	Age of Orientale Basin Composition of crust
7	Crater Copernicus	Impact melt on floor	Absolute age Composition of crust
8	Crater King	Impact melt on rim or floor	Composition of far-side crust Absolute age
9	Ancient crust	Near 30°N, 160°E	Composition Absolute age
10	South Pole-Aitken Basin massifs	South of Korolev, 21.5°S, 160°W	Composition of far-side crust Absolute age
11	Pre-late Imbrian mare basalt	Center of Schickard North of Balmer	Absolute age Composition
12	Early late Imbrian mare	Mare Marginis, in Ibn Yunus	Absolute age Composition (KREEP rich?)
13	Eratosthenian mare	Southwestern Mare Imbrium Surveyor 1 region, near 2.5°S, 43.5°W	Absolute age Calibration of color spectra
14	Central Mare Serenitatis	Between Bessel and Dawes	Calibration of color spectra (standard spectrum) Absolute age (near Imbrian-Eratostheian boundary)
15	Orientale Basin lobate ejecta	Near 53°S, 79°W	Impact melt or clastic ejecta?
16	Alpes Formation (knobby Imbrium Basin ejecta)	Southeast of Vallis Alpes near 45°N, 5°E	Impact melt/clastic content Composition of Imbrium ejecta
17	Apennine Bench Formation (planar deposits in Imbrium Basin)	Near 27°N, 8°W	KREEP-rich volcanic materials or impact melt? Absolute age Calibrate orbital geochemical data
18	Reiner Gamma Formation (irregular bright patch on mare)	Near 7.5°N, 59°W	Absolute age Magnetism involved in origin?
19	Fissured, crater floor deposits	Floor of Murchison, 1°W, 5°N	Ejected Imbrium Basin impact melt?

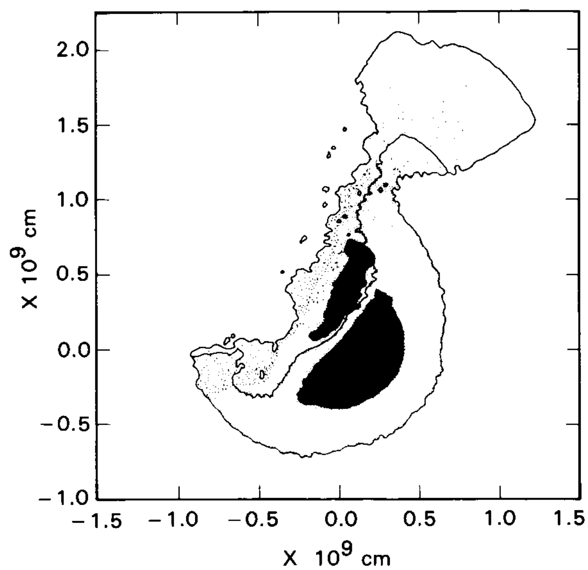
with Earth—were all seen by researchers as flawed, though each hypothesis had its tenacious supporters. The main problems with these models stem from inconsistencies with the Moon's composition and from dynamical considerations.

At the Conference on the Origin of the Moon, held in October 1984, an idea captured the imagination of the community, even though it had been around for almost a decade (Hartmann and Davis, 1975; Cameron and Ward, 1976). This hypothesis calls for the impact of a Mars-sized object with the growing Earth, flinging massive amounts of material into orbit around Earth (fig. 20). The Moon formed from this ring of debris. Although this idea has achieved some popularity, much research is needed to establish its veracity. In particular, we must establish how much material was actually placed into orbit, under what conditions enough debris was blasted into orbit, how much was vapor versus solid, and how much came from the fledgling Earth compared with the amount from the projectile during such an impact event. This last point is critical; preliminary calculations suggest that about half to almost all of the debris from which the Moon formed was derived from the impactor (see Hartmann et al., 1986). If these calculations are correct, then the collisional-ejection hypothesis does not straightforwardly explain the close relation between Earth and the Moon inferred from geochemical data. We also must assess the composition of the hypothetical impactor and understand the chemical effects of such an impact.

The collisional-ejection hypothesis has prompted new research into how the Moon formed, but its debut has not caused the demise of other ideas. The traditional hypotheses and their variants and the giant impact idea are more properly viewed as *processes* that operated during the formation of the Earth-Moon System. For example, a giant impact placing a ring of debris into orbit around Earth does not preclude additional accretion of material as depicted by coaccretion models. There seems to be an increasing appreciation of the complexity and synergism of processes operating during the formation of the terrestrial planets.



(a)



(b)

Figure 20. Results of two-dimensional computer simulations of the impact of a Mars-sized object with primitive Earth. Black areas are metallic iron, and stippled areas are silicates; stipple density is proportional to material density, which is initially that of molten silicate. Impact velocity is 12 km/s; calculation includes the effects of gravity. (a) About 250 seconds after impact; small jets are beginning to develop. (b) About 1500 seconds after impact; jet has expanded considerably and the most heated material (almost entirely vapor) will be lost, but the "neck" of the plume is likely to be trapped in Earth's orbit. (Courtesy of M. Kipp and H. J. Melosh).

THE FUTURE OF LUNAR SCIENCE

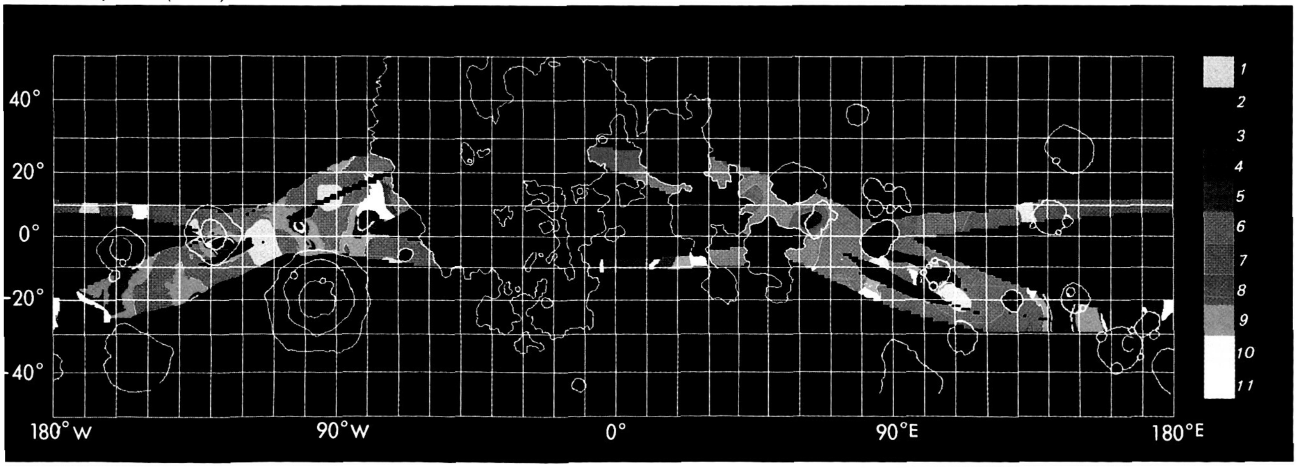
IMMEDIATE NEEDS

Support of Lunar Science

We have shown that the excellent quality of ongoing research into lunar science problems continues to produce new and sometimes startling results. We have found that the Moon is a body of unsuspected complexity (table 2); results of studies that reexamine "solved" issues raise new questions, more subtle and more complicated than the previous set. The results of such studies also provide a new conceptual framework within which other lunar data may be reevaluated. Such an intellectual synthesis in turn provides new directions for additional research.

In any field of science, advancement requires not only acquisition of new information to augment existing data, but also new ideas, perspectives, and techniques in the use of such data. This process may involve, for instance, a different way of utilizing data sets that may have been extant for several years. For example, Davis and Spudis (1985) have used the digital remote-sensing geochemical databases and results of lunar sample investigations to define petrologic map units in the lunar highlands (fig. 21). This technique utilizes chemical data in a way that has meaning

Figure 21. Map showing distribution of regional petrologic provinces on the Moon based on orbital data for thorium, titanium, and iron concentrations. Some units represent virtually pure rock types (e.g., unit 1 corresponds to pure anorthosite; unit 2 corresponds to pure norite or KREEP basalt); others represent quantified mixtures of such rock types. The technique used permits rapid classification of remotely sensed geochemical data into petrologic units. From Davis and Spudis (1985).



for the geologist; that is, it defines the spatial extent of inferred rock types. This example is cited to demonstrate that new and sometimes surprising discoveries are not only possible but probable through continued analysis of existing data.

We believe that continued support of lunar studies by NASA will yield new insights and better understanding of lunar geologic processes and history. The most recent lunar seismic velocity profile, based on reduction of all Apollo Passive Seismic Experiment arrival time data (Nakamura, 1983) has not yet been fully exploited in terms of its implications for lunar bulk composition and internal structure. The problems of understanding lunar paleomagnetism can now be directly addressed by a new concerted effort to understand the nature of ferromagnetic carriers in lunar materials. Such a study is crucial to our interpretation of lunar magnetism and also to our evaluation of the ancient core dynamo hypothesis (Runcorn, 1983), an idea that, if correct, has important implications for lunar bulk composition and hence origin. Major advances may be expected from continued work on the lunar sample collection as we continue to find new rock types and to study other samples with a new perspective (Lunar and Planetary Sample Team, 1985). Almost all of the current lunar research is of high quality, and it is our hope that these efforts will not only be supported, but encouraged.

Acquisition of New Data Prior to Lunar Geoscience Observer

To plan for the resumption of lunar exploration, we must acquire new data to support basic research and to provide crucial information. This effort includes Earth-based observations, theoretical modeling, experimental work, and lunar sample analysis.

Spectral data

One source of new data is Earth-based telescopic reflectance spectra. Analysis of the spectral characteristics of radiation (0.35 to 2.5 μm) reflected from the Moon provides constraints on the surface mineralogy, the crystal/glass ratio in the soil (maturity level), and the titanium content of mature mare surfaces. Fresh mare craters, mature mare surfaces, highland background material, and fresh highland craters each have characteristic spectral reflectance curves. Compositional inferences that can be made from variations within each class allow the mapping of distinct lithologic units on the lunar surface.

Analysis and interpretation of lunar spectral data have proven to be useful in solving a wide range of lunar problems. Recent examples include the following: (1) the identification of olivine as the dominant mafic mineral in the central peaks of Copernicus Crater (fig. 22; Pieters, 1982; Pieters and Wilhelms, 1985); (2) the determination that deposits of anorthosite are located on portions of the inner rings of both the Orientale (fig. 22) and Nectaris Basins (Spudis et al., 1984; Hawke et al., 1985); and (3) the determination that certain dark-haloed impact craters excavated mare basalt from ancient, pre-Imbrian mare deposits that had been covered with varied thicknesses of highlands debris (Hawke and Bell, 1981; Bell and Hawke, 1984). Continuation and expansion of spectral studies of the Moon will advance our understanding of surface compositions and processes, as well as support and complement the efforts of investigators in other disciplines. These studies are critical if we are to properly plan for and interpret the results from future missions such as the LGO.

More laboratory spectra of lunar samples are needed to calibrate properly the results of ground-based and spacecraft spectral studies. Many sample spectra were obtained in the early 1970s, and many new rock types have since been identified, yet few new sample spectra have been published and no such spectra are being collected now. The collection of lunar sample spectra should be an ongoing project. Mixtures of mafic minerals, plagioclase feldspar, and opaque minerals can simulate fresh lunar surficial materials. The results of these investigations of mineral mixture spectra are useful for studies of the Moon and other solar system bodies.

Cratering data

Our understanding of impact processes on the Moon has evolved by using a variety of approaches: experiment, theory, photogeology, and

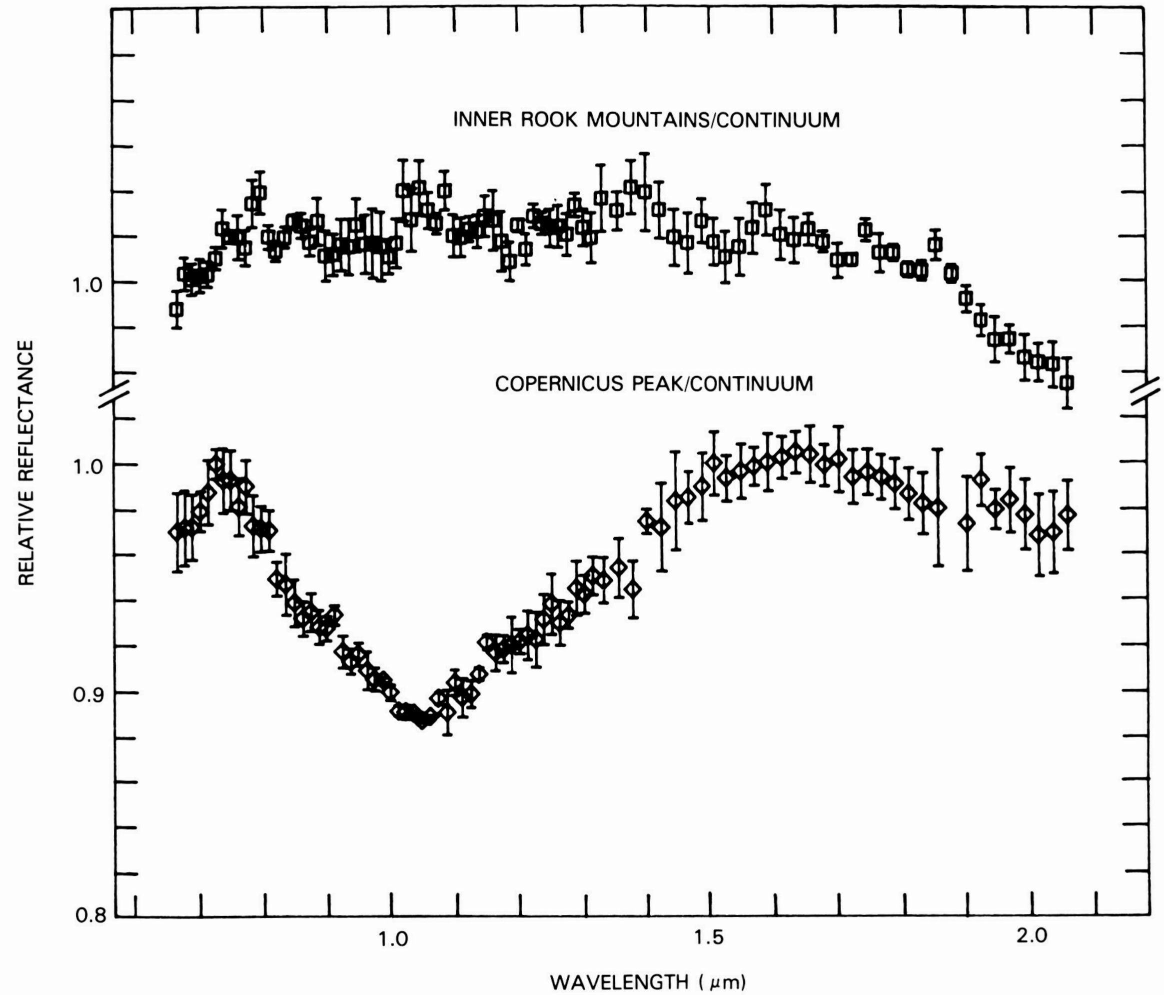
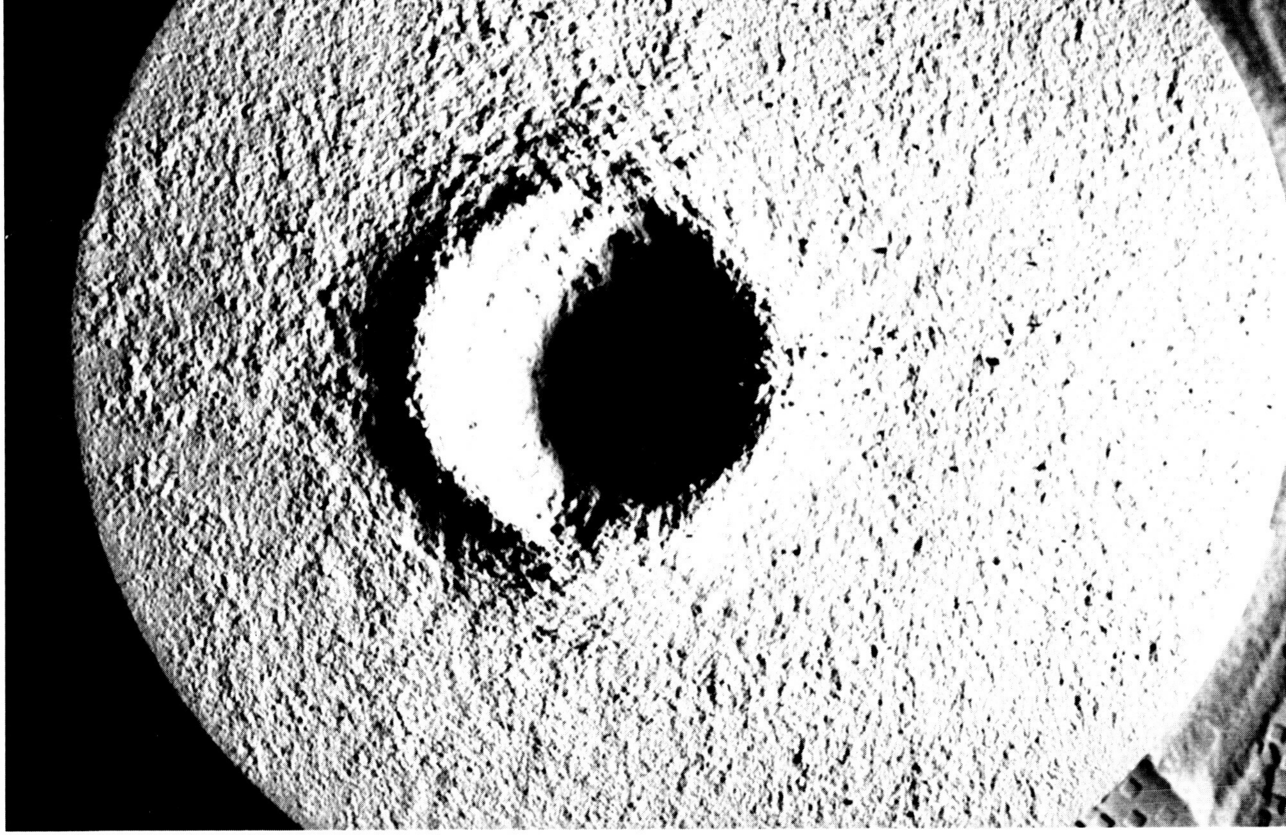
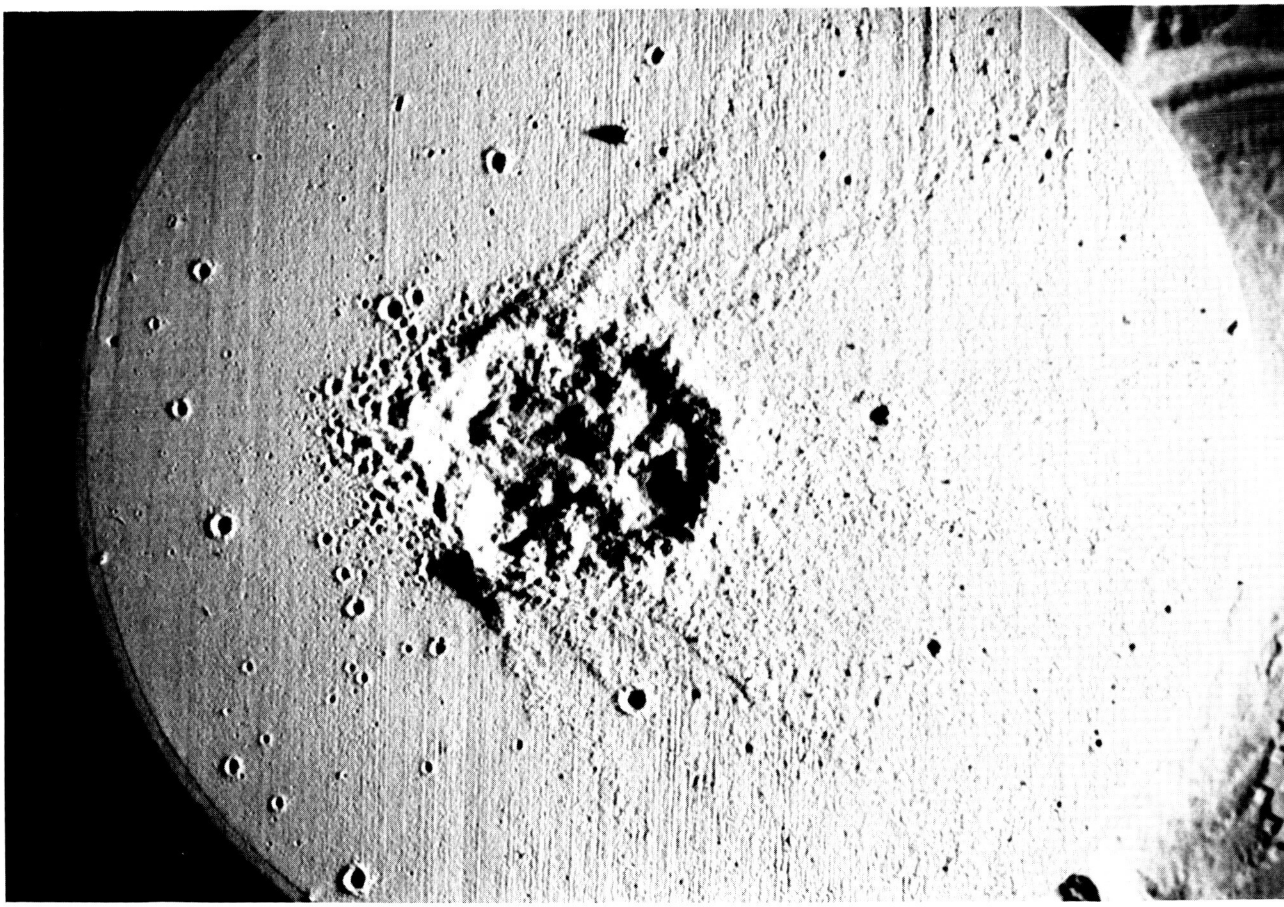


Figure 22. Near-infrared reflectance spectra for a small, very fresh crater located on a massif of the Inner Rook Mountains of Orientale Basin (Spudis et al., 1984) and for one of the central peaks of Copernicus Crater (Pieters, 1982). Spectra are residual absorption features produced as the ratio of reflectance spectrum to a continuum estimate. Broad multiple absorptions centered beyond 1 μm observed in the Copernicus peak spectrum indicate olivine. No absorption bands are seen in the Inner Rock Mountains spectrum, indicating the presence of shocked anorthosites.

terrestrial analogy. Continuation of these approaches is necessary to stimulate new questions and resolve existing ones. Experiments (fig. 23) and theoretical analyses that test the fundamental assumptions presently used must continue to be identified. For example, what is the effect of impact-generated melting and vaporization on the scaling laws established for relatively modest velocities (< 7 km/s)? How are magnetic fields generated by the impact process? What is the effect of oblique impact on cratering mechanics? What is the effect of impact-induced shock on a sample's spectral reflectance? What is the effect of large projectiles (> 10 km) and modest impact velocities (< 10 km/s) on the cratering flow field? Advances in electromagnetic railgun technology may permit experiments with much higher impact masses and velocities.

Fundamental studies of igneous processes

Our appreciation of the origin and evolution of the lunar crust can only be as good as our understanding of magmatic processes. Adequate support should be provided for experiments and studies of appropriate terrestrial analogs (for example, layered igneous intrusions). Deciphering the record of lunar igneous history and inferring the bulk composition and the nature of the interior of the Moon requires more information about the following: (1) the physics and chemistry of large bodies of magma; (2) phase equilibria in systems at low oxygen fugacities as appropriate to the Moon; (3) controls on trace-element partitioning among coexisting phases, including silicates, oxides, and metallic phases; (4) petrologic processes such as assimilation, including kinetic parameters amenable to numerical modeling; and (5) quantitative modeling of magma generation and transport (Wilson and Head, 1981). Although these are active areas of research in the terrestrial geology community, continued NASA support for such efforts is appropriate because of their importance to planetary problems and because NASA must ensure that the efforts are applied to those problems.

Lunar sample data

A discussion of the wealth of information still tied up in lunar samples is given in *Horizons and Opportunities in Lunar Sample Science* (Lunar and Planetary Sample Team, 1985). The key point is that, after more than a decade and a half of research, the treasure returned by Apollo still requires intensive study. Most of the rocks returned from the highlands are breccias, complex mixtures of many rock types. Nuggets of the ancient lunar crust occur in these rocks, and each year previously unidentified rock types are discovered, helping to extend our knowledge of the Moon. Futhermore, as analytical techniques improve (with funding now mostly from the National Science Foundation), lunar samples are restudied and new insights are obtained. Finally, good fortune brings us new pieces of the Moon in the form of lunar meteorites (fig. 24). Four such meteorites have now been discovered in Antarctica.

Cartographic products

The various cartographic products produced during the 1960s and 1970s, using Earth-based, Lunar Orbiter, and Apollo photography, proved to be of great importance for mission planning; support of geological, geochemical, and geophysical studies (fig. 25); and morphometric studies of craters, volcanic features, and other lunar landforms. These products include the Lunar Aeronautical Charts (LAC) 1:1,000,000-scale series, small-scale near-side and far-side maps, the Lunar Map (LM) series, and the Lunar Topographic Orthophotomap series. Unfortunately, the lunar mapping effort ceased in the late 1970s. To support ongoing research and to prepare for projected new missions, the lunar cartographic effort should continue at a level sufficient to meet the most critical needs of the science community. Among the most important new cartographic products needed are a revised 1:5,000,000-scale map of the lunar near side, large-scale topographic maps for features or landforms of special interest, additional 1:1,000,000-scale members of the LM series, high-resolution topographic profiles prepared from existing Apollo photography to support ongoing topical research, and a lunar digital-image database.

NEW UNMANNED MISSIONS

We have learned much about the Moon since the era of spacecraft exploration began in

Figure 23. Examples of experimental impact craters made at the NASA Ames Research Center vertical gun range facility. The top photograph shows an impact crater produced by a single-body, pyrex sphere 6.35 mm in diameter; the impact velocity was 2 km/s. The bottom photograph shows a crater formed by a dispersed projectile (7.6-cm-diameter cloud) impacting at 1.6 km/s at 45° to the vertical. Experiments such as these provide insight into cratering mechanics operating under a variety of conditions for direct comparison with lunar processes and landforms.

Figure 24. Meteorite Allan Hills 81005, collected in Antarctica in 1981. Petrologic and chemical studies indicate that it is a regolith breccia from the lunar highlands. Compositional data suggest that this Moon rock may have come from an area chemically different and distant from the Apollo and Luna landing sites. The startling discovery of a lunar meteorite (three more are now known) indicates that we may continue to get new lunar samples for study.

1959 (tables 1 and 2). The origins of the maria (volcanic basalt) and of most craters (impact) are settled. The approximate compositions of the Moon's crust and mantle and of many geologic units are far better known than before the space age. Representative deposits exposed at the surface have been dated on both the relative and absolute time scales, and the antiquity of the Moon's face has been established. Comparison of pre-1960 and current lunar literature quickly shows how far our knowledge has advanced.

Nevertheless, many important scientific questions remain unanswered. Although some problems can probably be solved by continued lunar sample analysis and experimental and field study on Earth, investigation of most of the remaining geologic questions requires resumption of lunar spaceflights. The largest gaps are in our knowledge of the subsurface structure and of the surface composition and stratigraphy outside the near-equatorial near side. Many of the needed data can be supplied by three classes of unmanned missions: global orbital surveys, sample returns, and surface geophysical stations. These relatively simple missions can be targeted intelligently with our current understanding of the Moon, incomplete as it is. With relatively little expense, they can not only greatly improve our understanding of the Moon's makeup and history, but they can also prepare the way for further, bolder steps, including the return to the Moon by humans.

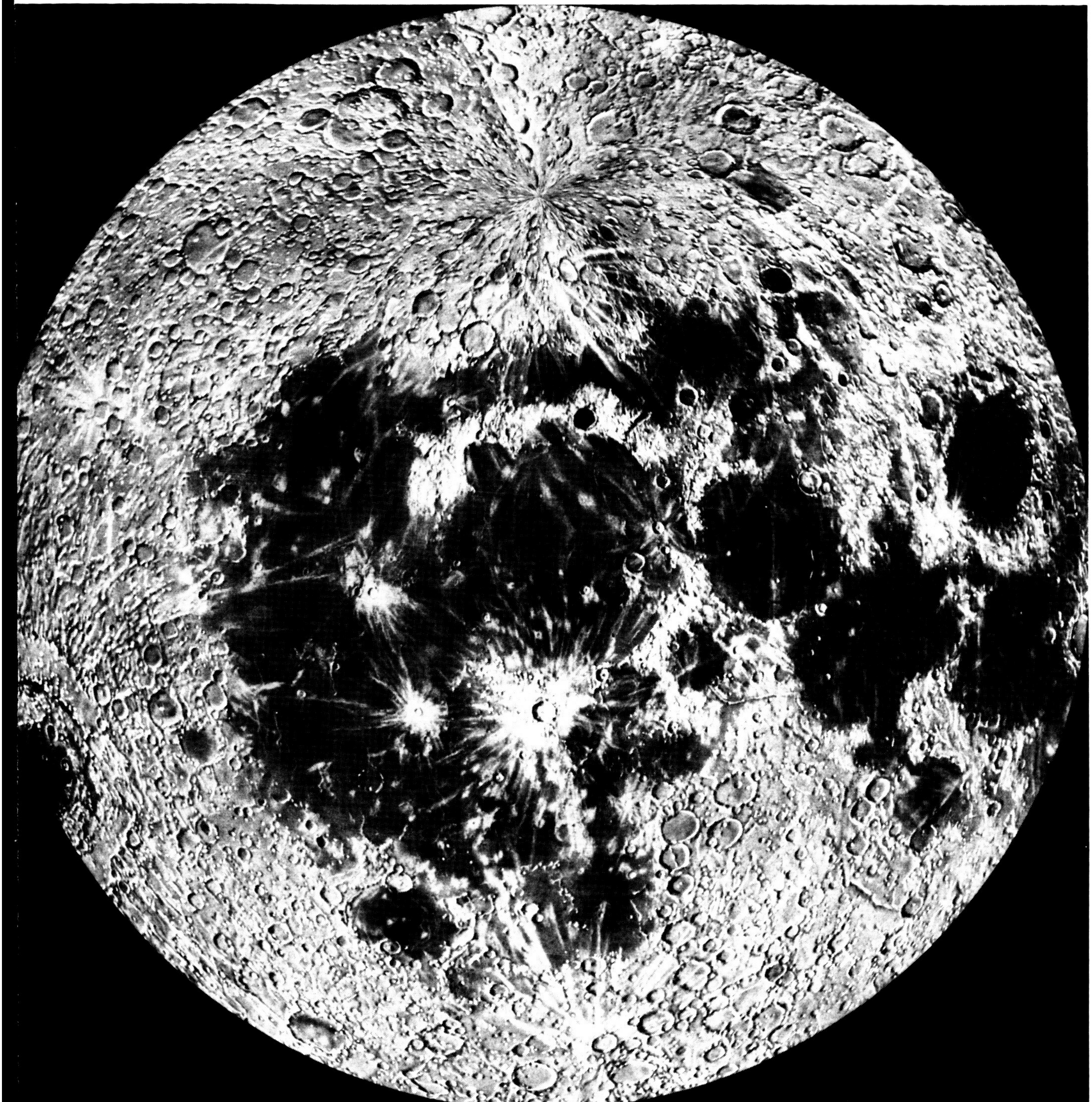


Figure 25. Lambert Equal-Area shaded relief map of the Moon centered on 35°N, 17°W (center of the Imbrium Basin). A digital-image file of cartographic data allows special lunar map projections to be made quickly and inexpensively to support topical scientific investigations. Such techniques will be particularly valuable to support studies of global data to be obtained by the Lunar Geoscience Observer Mission.

Lunar Geoscience Observer (Modified from Wilhelms, 1985)

A pressing requirement in lunar geoscience is to characterize the Moon as a global entity. The spectacular samples and other data returned by Apollo and the Soviet Lunas, and even other samples that might be obtained in the future, apply directly only to small areas. Their wider significance must be determined by extrapolations on the basis of global data. Yet such data are lacking.

Lunar Orbiters 4 and 5 (1967) provided indispensable photographic coverage of most of the Moon from their near-polar (85° inclination) orbits. Our current knowledge of the Moon would be incomplete without these missions (which were originally intended for detailed landing-site studies in the equatorial belt and not for reconnaissance purposes). The Lunar Orbiters, however, carried no geochemical or geophysical instruments. Apollos 15 to 17 (1971 to 1972) did carry such instruments, but the spacecraft were restricted to parts of the equatorial belt between latitudes 30°N and S. Thus, no geochemical and geophysical data exist for most of the Moon. A Lunar Geoscience Observer (LGO) placed in a near-polar orbit is needed to supply them (fig. 26).

At present, remote-sensing geochemical and mineralogical data, useful for extrapolating to large areas the compositional data obtained from returned samples, are available from only the small area overflown by Apollos 15 to 17 and, for the near side, from telescopic remote sensing. The LGO could readily obtain data in several wavelengths that could be used to determine the compositional variability of all the lunar maria. The estimated compositions of the basalts could then be correlated with their ages and with the sizes and inferred depths of the containing basins. The volumes, depths, and thermal histories of the mantle source zones of the basalts could be partly inferred from these correlations.

The terrae, which cover 83% of the Moon, suffer from an even more serious gap in geochemical knowledge. Terra materials constitute almost all of the volume of the lunar crust, yet they have been directly sampled at only five spots (by Apollos 14 to 17 and Luna 20). Because most terra materials are mixtures of the original igneous rock types, the remote-sensing data so far available have not closely specified the compositions of the unsampled remainder. This ignorance severely limits planetary scientists attempting to study the evolution of the crust and the origin of the Moon and the solar system. These data are also central to the purpose of an eventual and inevitable manned return to the Moon: resource exploitation. Basalts rich in titanium and iron and terra materials rich in aluminum and possibly chromium could be identified from orbit. Water trapped in permanently shadowed regions of the lunar poles (Arnold, 1979) could be detected by such a mission.

Except in a few small areas overflown at low altitudes, regional and local lunar gravity fields are poorly known. A major problem is the mass balance of basins. Gravity models are consistent with mascons (positive gravity anomalies) resulting from both mare basalt loading (Solomon and Head, 1980) and uplift of stratigraphically lower, dense materials (Phillips and Dvorak, 1981); however, we do not know if the gravity field was positive, negative, or neutral following basin formation but before filling by the basalt. Gravity anomaly measurements over far-side basins unfilled by mare basalt will answer this question.

Another problem only partly approachable with the existing data is the origin of the remanent magnetism found in lunar samples and recognized from orbit. As noted above, several hypotheses for the origin of the fields and the way the magnetism was acquired are still feasible; different ones may have applied at different stages of lunar history. Global measurements from orbit of the remanent magnetism will help determine whether the Moon possesses a core—a central question in considerations of lunar composition, thermal history, and origin.

The Lunar Orbiter program failed to photograph large parts of the Moon, particularly the poles, most of the limb regions on both

Figure 26. Artist's conception of the Lunar Geoscience Observer spacecraft in lunar orbit.

hemispheres, the far side at latitudes greater than about 40°N and S, and a zone between longitudes 100° and 120° W. Thus, any future global orbiter should include an imaging system. Global photography could fill gaps in lunar knowledge that are fundamental to the study of any planet. Gravity modeling, geodesy, thickness estimates of geologic units, spaceflight engineering and operations, and other important scientific and technical tasks depend on knowledge of topography. For the Moon, the heights of basin rims and other rings and the elevations of the contained maria are particularly significant, yet the topography of no basin has been completely determined. The topography of the Orientale Basin, which is the model for other basins because it is relatively young and large, is known only within wide limits. Accurate photogrammetry can be performed only for the illuminated parts of the Apollo groundtracks. Refinements of the rest of the topography of the near side still depend on telescopic selenodesy and radar modeling. The topography of the parts of the far side and the polar regions that were not overflown is almost completely unknown. The need for these basic data is obvious.

Stratigraphic analysis is also dependent on good photographs. Knowledge of the stratigraphic framework of near-surface rocks is a necessary prerequisite for extrapolation of the surface data from manned and unmanned sampling and geophysical probes to larger areas (Basaltic Volcanism Study Project, 1981; Wilhelms, 1984, in press). An understanding of the significance of the orbital geochemical and geophysical data also depends on knowledge of the stratigraphy. The lunar stratigraphy has been fairly well determined for the near side and central far side. However, we must obtain photographs at adequate resolution for stratigraphic analysis of many areas. Filling in the gap along the west limb is particularly important because it includes part of the Orientale Basin. The east limb includes the large and puzzling Crisium Basin, and the other poorly photographed zones include basins whose stratigraphic sequence and ring structure should be examined.

In summary, obtaining data on geochemistry, geophysics, topography, and stratigraphy—on a global scale—is a necessary step in the exploration of any planetary body. No small spot, however well explored, can reveal the global framework and history any more than it can on Earth. If we cannot understand the Moon as a whole, this most accessible of the relatively primitive planet-sized objects cannot fulfill its role as a comparative baseline for the terrestrial planets.

Sample Return (modified from Wilhelms, 1985)

We need additional samples from the Moon in order to solve many problems. Lunas 16, 20, and 24 proved the value of unmanned sample return from targets that, apparently, were not selected in advance except within broad selenographic limits. Despite the small sample size, they provided two absolute ages in the maria and one in the terra, added two types to the list of mare basalt compositions, and sampled terra material at a point remote from Apollo sites. A relatively inexpensive program of unmanned sample-returning spacecraft could yield significant advances if our current knowledge of lunar geology is applied to the selection of landing sites. Table 3 lists, as examples, 19 sites or groups of sites at which sampling missions could address the five categories of geologic questions discussed below. Data from each site could be extrapolated to larger areas by means of currently available or future (LGO) orbital remote-sensing data. Each probe is considered capable of returning a single bulk sample of regolith (1 to 2 kg) randomly selected from within the designated area.

Several more absolute ages are needed to calibrate the lunar stratigraphic column, particularly for basins (sites 1, 6, 10 and 15 to 17), young maria (sites 2, 13, and 14), and young craters (sites 7 and 8). Only the ages of the Imbrium Basin (3.85 billion years) and the Serenitatis Basin (3.87 billion years) and the questionable age of the Nectaris Basin (3.92 billion years) are available to date early lunar history. The highest priority is given here to dating the Nectaris Basin, whose relative age is well known and which, if securely dated, would therefore provide a needed calibration for the premare cratering rate (Wilhelms, in press). Dating of events in the last 3.0 billion years of lunar history is similar-

ly imprecise. Maria younger than 3.16 billion years (Apollo 12) have been dated relatively (Boyce, 1976; Schultz and Spudis, 1983) but not radiometrically, and the Apollo 12 basalt flows are hard to date on the relative time scale.

Although the origin of most lunar geologic units is now known to a good approximation, that of many highland plains and domelike hills is still questionable. These units should be sampled so that we can decide whether highland volcanism has occurred on the Moon (sites 3, 4, and 17). Also, some impact phenomena must be further explored, notably the relative volumes of impact-melt rock and clastic material in basin ejecta deposits (sites 15 to 17, and 19).

The remote-sensing data discussed above must be calibrated by "ground truth" at points of known stratigraphic context (sites 1, 6 to 10, and 16). Such extrapolation from small to large areas has proved to be the most efficient use of lunar sample data to address questions of global significance. Similar needs apply to the mare basalts; extrapolations from previously sampled color and age units could calibrate existing and future remotely sensed properties (sites 2, 5, and 12 to 14). Basalts appear to have formed in abundance before and near the end of the disruption by the early impact barrage (Schultz and Spudis, 1983), but their extent, compositional variability, and age spread are not known. This is a problem to be solved by directed sampling of certain breccias and thin plains units (sites 3?, 11, and 17?).

Global Surface Geophysical Network

Although gross properties of the lunar crust have been deduced by geophysical methods using the Apollo data sets, much remains to be done if knowledge of crustal composition and structure is to impose rigid constraints on lunar bulk composition, and hence on lunar origin models. Furthermore, evaluations of the evolution of the early lunar lithosphere remain incomplete and can be improved by the acquisition of new geophysical data in situ. Our ability to establish more accurately global lunar crustal density, thickness, and state of isostatic compensation is limited mainly by the lack of additional determinations of crustal thickness from seismology, combined with the poor global coverage of high-resolution gravity and topography measurements. Consequently, global spherical harmonic models of both gravity and topography are of reduced accuracy and are limited to wavelengths representative of features at basin scale or larger.

Although data returned from a polar-oribiting mission such as LGO will give information on the Moon's gravity and magnetic fields, detailed knowledge of the lunar interior awaits the installation of a global surface geophysical net. A relatively inexpensive system to establish such a network is described by Binder (1978). The SELENE concept is to emplace 16 geophysical stations composing four arrays at landing sites separated by 111° on a great circle. This layout produces a global tetrahedron such that any two arrays may measure the same seismic event. Each geophysical station would comprise a seismometer and heat flow experiment; a third optional instrument at each station could be a surface magnetometer, a mass spectrometer, or some other instrument. With an operational lifetime of at least 10 years, such a geophysical array would provide abundant data from the lunar interior. Among the questions to be addressed are the size, composition, and properties of a lunar core; the structure and composition of the mantle; variations in lunar crustal thickness and composition; and the origin of lunar paleomagnetism. The three-component effort of LGO, sample return, and surface network will allow us to characterize the Moon as a global entity.

RETURN TO THE MOON— A LUNAR BASE

The question of a permanent human presence on the Moon is really one of who and when, not if. Lunar science has the potential to properly evaluate a future prospect. In the valuable lead time that we have prior to a manned return to the Moon, continued lunar research will prepare us for the time when the Moon will really be a part of our neighborhood.

Most scenarios for lunar base development call for initial exploratory sorties before an operational facility is established. Data returned from the unmanned lunar missions described above

will be important for proper scientific planning, resource exploitation, and base site selection and operation. In scientific terms, the return of humans to the Moon will lead to new vistas of exporation about which we can only dream at present. An example of the types of advanced geologic exploration possible with an operational lunar base is given by Cintala et al. (1985). In this scientific daydream, a 4000-km traverse across the lunar near side (fig. 27) would give us the opportunity to study lunar processes in detail; such an information explosion would undoubtedly revolutionize planetary science in a way that would make the Apollo missions pale in scientific comparison.

When one considers that the science of geology has existed for only about 200 years, our progress in understanding the workings of Earth is amazing. Lunar geoscience, only about a tenth as old, has produced an equally astounding record. We have a long way to go in both fields, but considering how far we have come, what may we expect during the next 20 years?

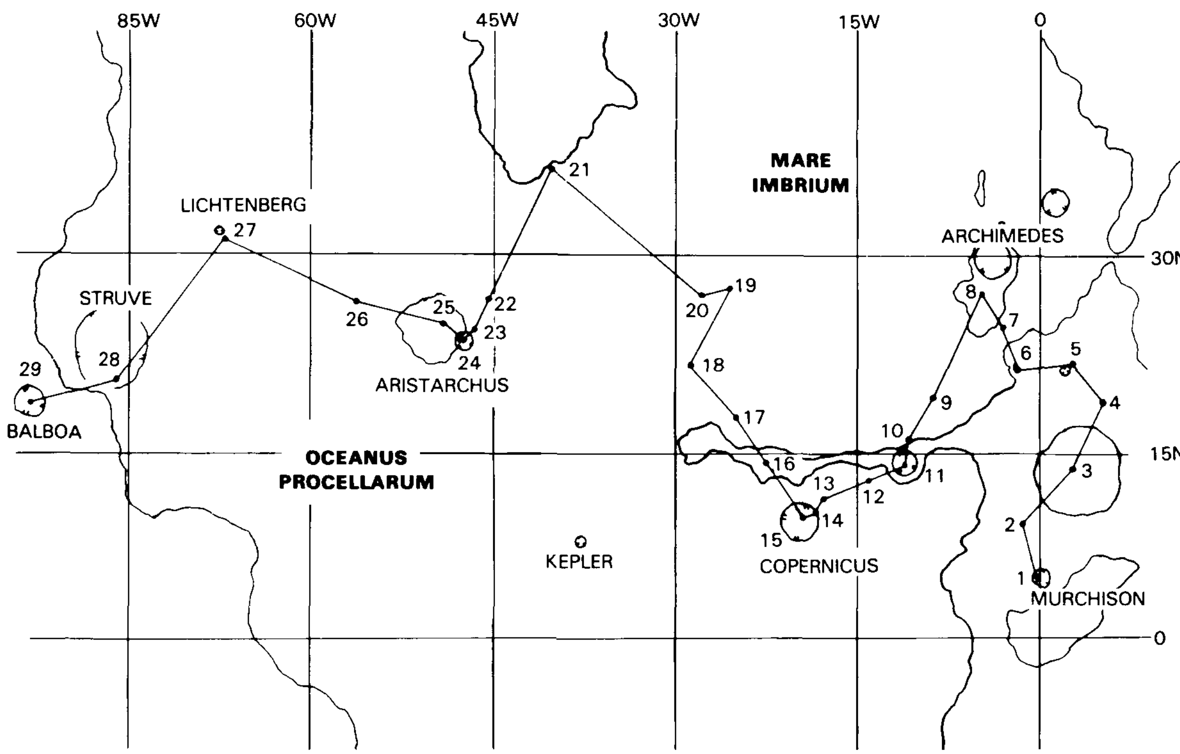


Figure 27. Map of a possible extended geologic traverse across the Imbrium-Procellarum region. Covering over 4000 km and encompassing 29 study sites, such a traverse would provide an abundance of data on lunar history and on a variety of geological processes. This is one example of possible scientific aspects of a permanent lunar base. See Cintala et al. (1985) for a detailed description of the scientific rationale for this traverse.

Summary

The Moon is of special interest among the many and diverse bodies of the solar system because it serves as a scientific baseline for understanding the terrestrial planets, its origin is closely tied to the early history of the Earth, and its proximity permits a variety of space applications such as mining and establishment of bases and colonies. The Moon is the only body other than Earth for which we have samples of known location, a variety of remote-sensing data, and geophysical information from surface instruments. This database has permitted reconstruction of the general features of lunar evolution. However, our knowledge of the Moon's surprisingly complex history remains incomplete; definitive answers to many questions regarding its origin and evolution require continued vigorous study.

Data acquisition and analysis have enabled us to make advances and identify remaining questions in many fields of lunar geoscience. A better—though still incomplete—understanding of the processes of impact cratering has improved our ability to estimate the relative ages of lunar geologic units, to model the excavation of large craters and basins, and to interpret the provenance of highland samples. The recently substantiated conclusion that mare volcanism probably endured for as long as 3 billion years, from 4.3 to less than 1.0 billion years ago, has important implications for lunar thermal history, cumulative bombardment history, and bulk composition. Although nonmare (KREEP) volcanism was less extensive than mare volcanism, regional deposits of KREEP basalts have been identified, and the history of KREEP volcanism remains a significant aspect of lunar petrogenesis. Studies of the timing and formation of tectonic features are leading to new evaluations of the lunar lithosphere and its changing thickness through time. The enlarged database from sample and remote-sensing studies has led to improved estimates of the Moon's bulk composition.

Although the 15-year-old concept that the Moon's crust originated in an early, global magma ocean explains crustal compositions and geology in a general way, the extent of the melting and the details of the processes that operated in such a large magma system remain obscure. We do not yet know the full range of rock types created during this melting episode and during the intensive highland magmatic activity that apparently occurred in the first few hundred million years of lunar history. Our understanding of mantle composition and structure has been advanced by the analysis of the seismic velocity profile, based on the complete Apollo seismic-net data, and by the study of ultramafic volcanic glasses, which may represent primary (unfractionated) magmas from deep in the mantle. The lateral and vertical variations of the mantle, however, are among the list of remaining unknowns.

The limited available sample data concerning magnetic paleointensity suggest thc existence of a relatively strong lunar magnetic field from 3.9 to 3.6 billion years ago. This analysis is complemented by the growing recognition that bright-swirl materials, which are geologically young and related to impact processes, are correlated with strong magnetic anomalies. The connection between impacts and the generation of magnetic fields that this correlation suggests is intriguing but unspecified, and the existence of a core dynamo and the core itself is still in question.

Among the most significant subjects of active research is a new hypothesis for lunar origin that appears to explain some previously puzzling dynamical relations and the apparent similarity in bulk composition of the Moon to Earth's mantle. In this scenario, a large (Mars-sized) planetesimal impacted Earth 4.6 billion years ago and ejected material into Earth's orbit; the material later coalesced as the Moon.

This promising progress suggests that lunar science should be given high priority in NASA's plans for solar system exploration. The current efforts of sample investigators, geologists, and geophysicists toward multidisciplinary approaches to the solution of outstanding problems should receive additional encouragement and support. In particular, a polar-orbiting spacecraft equipped with geologic, geochemical, and geophysical instruments (the proposed Lunar Geoscience Observer mission) should be flown as soon as possible. The geochemical, mineralogical, and geophysical data for the whole Moon returned by this mission will enable us to achieve a more detailed understanding of its geologic evolution. This mission should be followed by unmanned sample returns and by emplacement of a global surface geophysical net. Because of the valuable lead time remaining before establishment of a lunar base, we now have the opportunity to advance significantly our knowledge of the processes and history of this fascinating touchstone of planetary science, and of other planetary bodies, at a relatively modest cost.

References

Arnold, J. R. (1979) Ice in the lunar polar regions. *J. Geophys. Res.* 84:5659-5668.

Austin, M. G., Thomsen, J. M., Ruhl, S. F., Orphal, D. L., Borden, W. F., Larson, S. A., and Schultz, P. H. (1981) Z-model analysis of impact cratering: An overview. In *Multi-ring Basins* (P. H. Schultz and R. B. Merrill, eds.) *Proc. Lunar. Planet. Sci. 12A*, p. 197-206.

Baldwin, R. B. (1963) *The Measure of the Moon*. University of Chicago Press.

Basaltic Volcanism Study Project (1981) *Basaltic Volcanism on the Terrestrial Planets*. Pergamon Press, New York.

Bell, J. F., and Hawke, B. R. (1983) Recent comet impacts on the Moon? *Lunar and Planet. Sci.* **XIV**: 29-30.

Bell, J. F., and Hawke, B. R. (1984) Lunar dark-haloed impact craters: origin and implications for early mare volcanism. *J. Geophys. Res.* 89: 6899-6910.

Bianchi, R., Capaccioni, F., Cerroni, P., Coridini, M., Flamini, E., Hurren, P., Martelli, G., and Smith, P. M. (1984) Radio-frequency emissions observed during hypervelocity impact experiments. *Nature* 308:830-832.

Bills, B. G., and Ferrari, A. J. (1977) A harmonic analysis of lunar topography. *Icarus* 31:244-259.

Binder, A. B. (1978) Selene: Ein Mondlandungsprogramm mit unbemannten Sonden, eine wissenschaftliche Studie der deutschen Forschungsgemeinschaft. Keil, Federal Republic of Germany.

Binder, A. B. (1982a) The mare basalt magma source region and mare basalt magma genesis. *J. Geophys. Res.* 87:A37-A53.

Binder, A. B. (1982b) Post-Imbrian global lunar tectonism: evidence for an initially totally molten Moon. *Moon and Planets* 26:117-133.

Blackshear, W. T., and Gapcynski, J. P. (1977) An improved value for the lunar moment of inertia. *J. Geophys. Res.* 82:1699-1701.

Bogard, D. D., Morris, R. V., Hirsch, W. C., and Lauer, H. V. (1980) Depositional and irradiational history of the Hadley Rille core 15010/11. *Proc. Lunar Planet. Sci. Conf. 11*, p. 1511-1529.

Boyce, J. M. (1976) Ages of flow units in the lunar nearside maria based on Lunar Orbiter IV photographs. *Proc. Lunar Sci. Conf.* 7, p. 2717-2728.

Boyce, J. M., and Johnson, D. (1978) Ages of flow units in the far eastern maria and implications for basin-filling history. *Proc. Lunar Planet. Sci. Conf.* 9, p. 3275-3283.

Boyce, J. M., Dial, A. L., and Soderblom, L. A. (1974) Ages of lunar nearside light plains and maria. *Proc. Lunar Sci. Conf. 5*, p. 11-23.

Bratt, S. R., Solomon, S. C., Head, J. W., and Thurber, C. H. (1985) The deep structure of lunar basins: implications for basin formation and modification. *J. Geophys. Res.* 90:3049-3064.

Brett, R. (1975) Thickness of some lunar mare basalt flows and ejecta blankets based on chemical kinetic data. *Geochim. Cosmochim. Acta* 39:1135-1141.

Burnett, D. S., and Woolum, D. S. (1977) Exposure ages and erosion rates for lunar rocks. *Phys. Chem. Earth* 10:63-101.

Cameron, A. G. W., and Ward, W. (1976) The origin of the moon. *Lunar Science* **VII**:120-122.

Carlson, R. W., and Lugmair, G. W. (1979) Sm-Nd constraints on early lunar differentiation and the evolution of KREEP. *Earth Planet. Sci. Lett.* 45:123-132.

Cashore, J., and Woronow, A. (1985) A new Monte Carlo model of lunar megaregolith development. Proc. Lunar Planet. Sci. Conf. 15, in *J. Geophys. Res.* 90:C811-C815.

Chao, E. C. T., Hodges, C. A., Boyce, J. M., and Soderblom, L. A. (1975) Origin of lunar light plains. *J. Res. U.S. Geol. Survey* 3:379-392.

Chapman, C. R., Mosher, J., and Simmons, G. (1970) Lunar cratering and erosion from Orbiter 5 photographs. *J. Geophys. Res.* 75:1445-1446.

Chapman, C. R., Aubele, J., Roberts, W. J., and Cutts, J. A. (1979) Subkilometer craters: origins, ages, processes of degradation and implications for mare basalt petrogenesis. *Lunar Planet. Sci.* **X**:190-191.

Charette, M. P., Taylor, S. R., Adams, J. B., and McCord, T. B. (1977) The detection of soils of Fra Mauro basalt and anorthositic gabbro composition in the lunar highlands by remote spectral reflectance techniques. *Proc. Lunar Sci. Conf.* 8, p. 1049-1061.

Cintala, M. J. (1979) Mercurian crater rim heights and some interplanetary comparisons. *Proc. Lunar Planet. Sci. Conf. 10*, p. 2635-2650.

Cintala, M. J., Spudis, P. D., and Hawke, B. R. (1985) Advanced geologic exploration supported by a lunar base: a traverse across the Imbrium-Procellarum region of the Moon. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.). Lunar and Planetary Institute Press, Houston, p. 223-238.

Cisowski, S. M., Collinson, D. W., Runcorn, S. K., Stephenson, A., and Fuller, M. (1983) A review of lunar paleointensity data and implications for the origin of lunar magnetism. Proc. Lunar Planet. Sci. Conf. 13, in *J. Geophys, Res.* 88:A691-A704.

Clayton, R. N., and Thiemans, M. H. (1980) Lunar nitrogen: evidence for secular change in the solar wind. In *Proceedings of the Conference on the Ancient Sun* (R. Pepin, J. Eddy, and R. Merrill, eds.). Pergamon Press, New York, p. 463-473.

Collinson, D. W. (1984) On the existence of magnetic fields on the moon between 3.6 Ga ago and the present. *Phys. Earth Planet. Int.* 32:102-116.

Conel, J. E., and Morton, J. B. (1975) Interpretation of lunar heat flow data. *The Moon* 14:263-289.

Croft, S. K. (1980) Cratering flow fields: implications for the excavation and transient expansion stages of crater formation. *Proc. Lunar Planet. Sci. Conf. 11*, p. 2347-2378.

Croft, S. K. (1981a) The excavation stage of basin formation: a qualitative model. In *Multi-ring Basins* (P. H. Schultz and R. B. Merrill, eds.). *Proc. Lunar Planet. Sci. 12A*, p. 207-225.

Croft, S. K. (1981b) The modification stage of basin formation: conditions of ring formation. In *Multi-ring Basins* (P. H. Shultz and R. B. Merrill, eds.). *Proc. Lunar Planet. Sci.* 12A, p. 227-257.

Davis, P. A., and Spudis, P. D. (1985) Petrologic province maps of the lunar highlands derived from orbital geochemical data. Proc. Lunar Planet. Sci. Conf. 16, in *J. Geophys. Res.* 90:D61-D74.

De Hon, R. A. (1979) Thickness of the western mare basalts. *Proc. Lunar Planet. Sci. Conf. 10*, p. 2935-2955.

Delano, J. W. (1979) Apollo 15 green glass: chemistry and possible origin. Proc. Lunar Planet. Sci Conf. 10, p. 275-300.

Delano, J. W. (1980) Chemistry and liquidus phase relations of Apollo 15 red glass: implications for the deep lunar interior. Proc. Lunar Planet. Sci. Conf. 11, p. 251-288.

Delano, J. W. (1986) Pristine lunar glasses: criteria, data, and implications. Proc. Lunar Planet. Sci. Conf. 16, in *J. Geophys Res.* 91:D201-D213.

Dickinson, T., Taylor, G. J., Keil, K., Schmitt, R. A., Hughes, S. S. and Smith, M. R. (1985) Apollo 14 aluminous mare basalts and their possible relationship to KREEP. Proc. Lunar Planet. Sci. Conf. 15, in *J. Geophys. Res.* 90:C365-C374.

Drake, M. J. (1986) Is lunar bulk material similar to Earth's mantle? In *The Origin of the Moon* (W. K. Hartmann, R. J. Phillips, and G. J. Taylor, eds). Lunar and Planetary Institute, Houston, p. 105-124.

Drozd, R. J., Hohenberg, C. M., Morgan, C. J., Podosek, F. A., and Wroge, M. L. (1977) Cosmic-ray exposure history at Taurus-Littrow. *Proc. Lunar Sci. Conf.* 8, p. 3027-3043.

Dyal, P., Parkin, C. W., and Daily, W. D. (1976) Structure of the lunar interior from magnetic field measurements. *Proc. Lunar Sci. Conf.* 7, p. 3077-3096.

Eggleton, R. E. (1981) Map of the impact geology of the Imbrium basin of the Moon. In *Geology of the Apollo 16 area, Central Lunar Highlands.* U.S. Geological Survey Professional Paper 1048, plate 12.

Fink, J., Gault, D., and Greeley, R. (1984) The effect of viscosity on impact cratering and possible applications to the icy satellites of Saturn and Jupiter. *J. Geophys. Res.* 89: 417-423.

Fuller, M. (1974) Lunar magnetism. *Rev. Geophys. Space Phys.* 12:23-70.

Gault, D. E. (1970) Saturation and equilibrium conditions for impact cratering on the lunar surface: criteria and implications. *Radio Sci.* 5:273-291.

Gault, D. E., and Sonett, C. P. (1982) Laboratory simulation of pelagic astroidal impact: atmospheric injection, benthic topography and the surface wave radiation field. *Geological Society of America Special Paper 190*, p. 69-92.

Gault, D. E., and Wedekind, J. S. (1977) Experimental hypervelocity impact into quartz sand. II. Effects of gravitational acceleration. In *Impact and Explosion Cratering* (D. J. Roddy, R. O. Pepin, and R. B. Merrill, eds.). Pergamon Press, New York, p. 1231-1244.

Gault, D. E., Guest, J. E., Murray, J. B., Dzurisin, D., and Malin, M. C. (1975) Some comparisons of impact craters on Mercury and the Moon. *J. Geophys. Res.* 80:2444-2460.

Goins, N. R., Dainty, A. M., and Toksoz, M. N. (1981a)

Structure of the lunar crust at highland site Apollo 16. *Geophys. Res. Lett.* 8:29-32.
Goins, N. R., Dainty, A. M., and Toksoz, M. N. (1981b) Lunar seismology: the internal structure of the moon. *J. Geophys. Res.* 86:5061-5074.
Golombek, M. P. (1979) Structural analysis of lunar grabens and the shallow crustal structure of the Moon. *J. Geophys. Res.* 84:4657-4666.
Greeley, R., and Gault, D. (1970) Precision size-frequency distributions of craters for 12 selected areas of the lunar surface. *The Moon* 2:10-77.
Grieve, R. A. F. (1980) Cratering in the lunar highlands: some problems with the process, record and effects. *Proc. Conf. Lunar Highlands Crust* (J. J. Papike and R. B. Merrill, eds.). Pergamon Press, New York, p. 173-196.
Grieve, R. A. F., and Garvin, J. F. (1984) A geometric model for excavation and modification at terrestrial simple impact craters. *J. Geophys. Res.* 89:11561-11572.
Grieve, R. A. F., Robertson, P. B., and Dence, M. R. (1981) Constraints on the formation of ring impact structures, based on terrestrial data. In *Multi-ring basins.* (P. H. Shultz and R. B. Merrill, eds.). *Proc. Lunar Planet. Sci. 12A*, p. 37-57.
Grove, T., and Walker, D. (1977) Cooling histories of Apollo 15 quartz-normative basalts. *Proc. Lunar Sci. Conf.* 8, p. 1501-1520.
Guest, J. E., and Murray, J. B. (1976) Volcanic features of the nearside equatorial lunar maria. *J. Geol. Soc. London* 132:251-258.
Guinness, E. A., and Arvidson, R. E. (1977) On the constancy of the lunar cratering flux over the past 3.3 $\times 10^9$ yr. *Proc. Lunar Sci. Conf.* 8, p. 3475-3494.
Haines, E. L., and Metzger, A. E. (1980) Lunar highland crustal models based on iron concentrations: isostasy and center-of-mass displacement. *Proc. Lunar Planet. Sci. Conf. 11*, p. 689-718.
Hall, J. L., Solomon, S. C., and Head, J. W. (1981) Lunar floor-fractured craters: evidence for viscous relaxation of crater topography. *J. Geophys. Res.* 86: 9537-9552.
Hartmann, W. K. (1973) Ancient lunar mega-regolith and subsurface structure. *Icarus* 18:634-636.
Hartmann, W. K. (1984) Does crater "saturation equilibrium" occur in the solar system? *Icarus* 60:56-74.
Hartmann, W. K., and Davis, D. R. (1975) Satellite-sized planetesimals and lunar origin. *Icarus* 24:504-515.
Hartmann, W. K., and Wood, C. A. (1971) Moon: origin and evolution of multi-ring basins. *The Moon* 3:4-78.
Hartmann, W. K., Phillips, R. J., and Taylor, G. J. (eds.) (1986) *The Origin of the Moon.* Lunar and Planetary Institute, Houston.
Hawke, B. R., and Bell, J. F. (1981) Remote sensing studies of lunar dark halo craters: preliminary results and implications for early volcanism. *Proc. Lunar Planet. Sci. Conf. 12B*, p. 665-678.
Hawke, B. R., and Head, J. W. (1977) Impact melt on lunar crater rims. In *Impact and Exposion Cratering* (D. J. Roddy, R. O. Pepin, and R. B. Merrill, eds.). Pergamon Press, New York, p. 815-841.
Hawke, B. R., and Head, J. W. (1978) Lunar KREEP volcanism: geologic evidence for history and mode of emplacement. *Proc. Lunar Planet. Sci. Conf.* 9, p. 3285-3309.
Hawke, B. R., and Spudis, P. D. (1980) Geochemical anomalies on the eastern limb and farside of the Moon. *Proc. Conf. Lunar Highlands Crust* (J. J. Papike and R. B. Merrill, eds.). Pergamon Press, New York, p. 467-481.
Hawke, B. R., Lucey, P. G., Bell, J. F., Owensby, P. D., Spudis, P. D., and Davis, P. A. (1985) Spectra studies of the highlands around the Nectaris basin: preliminary results. *Lunar Planet. Sci.* **XVI**:329-330.
Hawke, B. R., Spudis, P. D., and Clark, P. E. (1985) The origin of selected lunar geochemical anomalies: implications for early volcanism and the formation of light plains. *Earth, Moon, and Planets* 32:257-273.
Head, J. W. (1976) Lunar volcanism in space and time. *Rev. Geophys. Space Phys.* 14:265-300.
Head, J. W. (1977) Some geologic observations concerning lunar geophysical models. In *The Soviet-American Conference on the Cosmochemistry of the Moon and Planets* (J. H. Pomeroy and N. J. Hubbard, eds.). NASA SP-370, U.S. Government Printing Office, Washington, D.C., p. 407-416.
Head, J. W. (1981) Lava flooding of ancient planetary crusts: geometry, thickness and volumes of flooded lunar impact basins. *Moon and Planets* 26:61-88.
Heiken, G. H., McKay, D. S., and Brown, R. W. (1974) Lunar deposits of possible pyroclastic origin. *Geochim. Cosmochim. Acta* 38:1703-1718.
Hess, P. C., Rutherford, M. J., Guillemette, R. N., Ryerson, F. J., and Tuchfeld, H. A. (1975) Residual products of fractional crystallization of lunar magmas: an experimental study. *Proc. Lunar Sci. Conf.* 6, p. 895-909.
Hide, R. (1972) Comments on the moon's magnetism. *The Moon* 4:39.
Holsapple, K. A. (1981) Coupling parameters in cratering. *EOS, Trans. Amer. Geophys. Union* 62: 944.
Hood, L. L. (1986) Geophysical constraints on the lunar interior. In *The Origin of the Moon* (W. Hartman, R. Phillips, and G. J. Taylor, eds.). Lunar and Planetary Institute, Houston, p. 361-410.
Hood, L. L., and Vickery, A. (1984) Magnetic field amplification and generation in hypervelocity meteoroid impacts with application to lunar paleomagnetism. Proc. Lunar Planet. Sci. Conf. 15, in *J. Geophys. Res.* 89:C211-C223.
Hood, L. L., Herbert, F., and Sonett, C. P. (1982) The deep lunar electrical conductivity profile: structural and thermal inferences. *J. Geophys. Res.* 87:5311-5326.
Hörz, F. (1977) Impact cratering and regolith dynamics. *Phys. Chem. Earth* 10:3-15.
Hörz, F. (1978) How thick are lunar mare basalts? *Proc.*

Lunar Planet. Sci. Conf. 9, p. 3311-3331.
Hörz, F., Gibbons, R. V., Hill, R. E., and Gault, D. E. (1976) Large scale cratering of the lunar highlands: some Monte Carto model considerations. *Proc. Lunar Sci. Conf.* 7, p. 2931-2945.
Hörz, F., Ostertag, R., and Rainey, D. A. (1983) Bunte breccia of the Ries: continuous deposits of large craters. *Rev. Geophys. Space Phys.* **21**:1667-1725.
Howard, K. A., and Wilshire, H. G. (1975) Flows of impact melt at lunar craters. *J. Res. U.S. Geol. Survey* **3**:237-251.
Howard, K. A., Head, J. W., and Swann, G. A. (1972) Geology of Hadley Rille. *Proc. Lunar Sci. Conf.* 3, p. 1-14.
Howard, K. A., Wilhelms, D. E., and Scott, D. H. (1974) Lunar basin formation and highland stratigraphy. *Rev. Geophys. Space Phys.* **12**:309-327.
Ivanov, B. A. (1976) The effect of gravity on crater formation: thickness of ejecta and concentric basins. *Proc. Lunar Sci. Conf.* 7, p. 2947-2965.
James, O. B. (1981) Petrologic and age relations of the Apollo 16 rocks: implications for the subsurface geology and the age of the Nectaris basin. *Proc. Lunar Planet. Sci. Conf. 12B*, p. 209-233.
James, O. B., and Hörz, F. (eds.) (1981) *Workshop on Apollo 16*. LPI Technical Report 81-01. The Lunar and Planetary Institute, Houston.
Kaula, W. M., Schubert G., Lingenfelter, R. E., Sjogren, W. L., and Wollenhaupt, W. R. (1974) Apollo laser altimetry and inferences as to lunar structure. *Proc. Lunar Sci. Conf.* 5, p. 3049-3058.
Kieffer, S. W., and Simonds, C. H. (1980) The role of volatiles and lithology in the impact cratering process. *Rev. Geophys. Space Phys.* **18**:143-181.
Langseth, M. G., Keihm, S. J., and Peters, K. (1976) Revised lunar heat-flow values. *Proc. Lunar Sci. Conf.* 7, p. 3143-3171.
Liebermann, R. C., and Ringwood, A. E. (1976) Elastic properties of anorthite and the nature of the lunar crust. *Earth Planet. Sci. Lett.* **31**:69-74.
Longhi, J. (1978) Pyroxene stability and the composition of the lunar magma ocean. *Proc. Lunar Planet. Sci. Conf.* 9, p. 285-306.
Longhi, J. (1980) A model of early lunar differentiation. *Proc. Lunar Planet. Sci. Conf. 11*, p. 289-315.
Longhi, J. (1981) Preliminary modeling of high-pressure partial melting: implications for early lunar differentiation. *Proc. Lunar Planet. Sci. Conf. 12B*, p. 1001-1018.
Longhi, J., and Boudreau, A. E. (1979) Complex igneous processes and the formation of the primitive lunar crustal rocks. *Proc. Lunar Planet. Sci. Conf. 10*, p. 2085-2105.
Lucchitta, B. K. (1976) Mare ridges and related highland scarps—result of vertical tectonism? *Proc. Lunar Sci. Conf.* 7, p. 2761-2782.
Lucchitta, B. K., and Sanchez, A. (1975) Crater studies in the Apollo 17 region. *Proc. Lunar Sci. Conf.* 6, p. 2427-2441.
Lucchitta, B. K., and Watkins, J. A. (1978) Age of graben systems on the Moon. *Proc. Lunar Planet. Sci. Conf.* 9, p. 3459-3472.
Lunar and Planetary Sample Team (LAPST) (1985) *Horizons and Opportunities in Lunar Sample Science*. LPI Technical Report 85-04. Lunar and Planetary Institute, Houston.
Mason, R., Guest, J. E., and Cooke, G. N. (1976) An Imbrium pattern of graben on the Moon. *Proc. Geol. Assoc. London* **87**:161-168.
Masursky, H., Colton, G. W., and El-Baz, F. (eds.) (1978) *Apollo Over the Moon*. NASA SP-362, U.S. Government Printing Office, Washington, D.C.
Maurer, P., Eberhardt, P., Geiss, J., Grögler, N., Stettler, A., Brown, G. M., Peckett, A., and Krähenbuhl, U. (1978) Pre-Imbrian craters and basins: ages, compositions and excavation depths of Apollo 16 breccias. *Geochim. Cosmochim. Acta* **42**:1687-1720.
Maxwell, D. E. (1977) Simple Z-model of cratering, ejection and overturned flap. In *Impact and Explosion Cratering* (D. J. Roddy, R. O. Pepin, and R. B. Merrill, eds.). Pergamon Press, New York, p. 1003-1008.
Maxwell, T. A., and Phillips, R. J. (1978) Stratigraphic correlation of the radar-detected substrate interface in Mare Crisium. *Geophys. Res. Lett.* **9**:811-814.
Melosh, H. J. (1981) Atmospheric breakup of terrestrial impactors. In *Multi-ring Basins* (P. H. Shultz and R. B. Merrill, eds.). *Proc. Lunar Planet. Sci. 12A*, p. 29-36.
Metzger, A. E., Haines, E. L., Parker, R. E., and Radocinski, R. G. (1977) Thorium concentrations in the lunar surface. I. Regional values and crustal content. *Proc. Lunar Sci. Conf.* 8, p. 949-999.
Milton, D. (1968) Geologic map of the Theophilus quadrangle of the Moon. U.S. Geological Survey Map I-546.
Moore, H. J., Lugn, R. V., and Newman, E. B. (1974) Some morphometric properties of experimentally cratered surfaces. *J. Res. U.S. Geol. Survey* **2**: 279-288.
Morris, R. V. (1978) The surface exposure (maturity) of lunar soils: some concepts and I_s/FeO compilation. *Proc. Lunar Planet. Sci. Conf.* 9, 2287-2297.
Morrison, R. H., and Oberbeck, V. R. (1978) A composition and thickness model for lunar impact crater and basin deposits. *Proc. Lunar Planet. Sci. Conf.* 9, p. 3763-3785.
Muehlberger, W. R. (1974) Structural history of southeastern Mare Serenitatis and adjacent highlands. *Proc. Lunar Sci. Conf.* 5, p. 101-110.
Muller, P. M., and Sjogren, W. L. (1968) Mascons: Lunar mass concentrations. *Science* **161**:680-684.
Nakamura, Y. (1983) Seismic velocity structure of the lunar mantle. *J. Geophys. Res.* **88**:677-686.
Nakamura, Y., Latham, G., Lammlein, D., Ewing, M., Duennebier, F., and Dorman, J. (1974) Deep lunar interior inferred from recent seismic data *Geophys. Res. Lett.* **1**:137-140.

Nakamura, Y., Latham, G. V., and Dorman, H. J. (1982) Apollo lunar seismic experiment—final summary. Proc. Lunar Planet Sci. Conf. 13, in *J. Geophys. Res.* 87:A117-A123.

Neukum, G., and Horn, P. (1976) Effects of lava flows on lunar crater populations. *The Moon* 15:205-222.

Neukum, G., König, B., Fechtig, H., and Storzer, D. (1975) Cratering in the Earth-Moon system: consequences for age determination by crater counting. *Proc. Lunar Sci. Conf. 6,* 2597-2620.

Newsom, H. E. (1984) The lunar core and the origin of the moon. *EOS* 65:369-370.

Oberbeck, V. R. (1975) The role of ballistic erosion and sedimentation in lunar stratigraphy. *Rev. Geophys. Space Phys.* 13: 337-362.

O'Hara, M. J., Biggar, G. M., Richardson, S. W., Ford, C. E., Jamieson, B. G. (1970) The nature of seas, mascons and the lunar interior in the light of experimental studies. Proc. *Apollo 11 Lunar Sci. Conf.* Pergamon Press, New York, p. 695-710.

O'Hara, M. J., Humphries, D. J., and Waterston, S. (1975) Petrogenesis of mare basalts: implications for chemical, mineralogical and thermal models for the Moon. *Proc. Lunar Sci. Conf. 6,* p. 1043-1055.

O'Keefe, J. D., and Ahrens, T. J. (1981) Impact cratering: the effect of crustal strength and planetary gravity. *Rev. Geophys. Space Phys.* 19: 1-12.

Orphal, D. L. (1977a) Calculations of explosion cratering. I. The shallow-buried nuclear detonation JOHNIE BOY. In *Impact and Explosion Cratering* (D. J. Roddy, R. O. Pepin, and R. B. Merrill, eds.). Pergamon Press, New York, p. 897-906.

Orphal, D. L. (1977b) Calculations of explosion cratering. II. Cratering mechanics and phenomenology. In *Impact and Explosion Cratering* (D. J. Roddy, R. O. Pepin, and R. B. Merrill, eds.) Pergamon Press, New York, p. 907-918.

Orphal, D. L., Borden, W. F., Larson, S. A., and Schultz, P. H. (1980) Impact melt generation and transport. *Proc. Lunar Planet. Sci. Conf. 11,* p. 2309-2323.

Pepin, R. O. (1980) Rare gases in the past and present solar wind. *Proceedings of the Conference on the Ancient Sun* (R. O. Pepin, J. Eddy, and R. B. Merrill, eds). Pergamon Press, New York, p. 411-421.

Phillips, R. J., and Dvorak, J. (1981) The origin of lunar mascons: analysis of the Bouguer gravity associated with Grimaldi. In *Multi-ring Basins* (P. H. Schultz and R. B. Merrill, eds.) *Proc. Lunar Planet. Sci.* 12A, p. 91-106.

Pieters, C. M. (1982) Copernicus crater central peak: lunar mountain of unique composition. *Science* 215:59-61.

Pieters, C. M., and Wilhelms, D. E. (1985) Origin of olivine at Copernicus. Proc. Lunar Planet. Sci. Conf. 15, in *J. Geophys. Res.* 89:C415-C420.

Pieters, C. M., Adams, J. B., Mouginis-Mark, P. J., Zisk, S. H. Smith, M. O., Head, J. W., and McCord, T. B. (1985) The nature of crater rays: the Copernicus example. *J. Geophys. Res.* 90:12393-12413.

Pike, R. J. (1980) Geometric interpretation of lunar craters. U.S. Geological Survey Professional Paper 1046-C.

Rasmussen, K. L., and Warren, P. H. (1985) Megaregolith thickness, heat flow, and the bulk composition of the moon. *Nature* 313:121-124.

Rhodes, J. M. (1977) Some compositional aspects of lunar regolith evolution. *Phil. Trans. Royal Soc. London* A285:293-301.

Ringwood, A. E. (1979) *Origin of the Earth and Moon.* Springer-Verlag, New York.

Ringwood, A. E., and Essene, E. (1970) Petrogenesis of Apollo 11 basalts, internal constitution and origin of the moon. *Proc. Apollo 11 Lunar Sci. Conf.* Pergamon Press, New York, p. 769-799.

Roddy, D. J., Schuster, S. H., Kreyenhagen, K. N., and Orphal, D. L. (1980) Computer code simulations of the formation of Meteor Crater, Arizona: calculations MC-1 and MC-2. *Proc. Lunar Planet. Sci. Conf. 11,* p. 2275-2308.

Roedder, E. (1978) Silicate liquid immiscibility in magmas and in the system K_2O-FeO-Al_2O_3-SiO_2: an example of serendipity. *Geochim. Cosmochim. Acta* 42: 1597-1617.

Roedder, E., and Weiblen, P. W. (1970) Lunar petrology of silicate melt inclusions, Apollo 11 rocks. *Proc. Apollo 11 Lunar Sci. Conf.* Pergamon Press, New York, p. 801-837.

Runcorn, S. K. (1983) Lunar magnetism, polar displacement and primeval satellites in the earth-moon system. *Nature* 304:589-596.

Russell, C. T., Coleman, P. J., Jr., and Goldstein, B. E. (1981) Measurements of the lunar induced magnetic moment in the geomagnetic tail: evidence for a lunar core. *Proc. Lunar Planet. Sci. Conf. 12B,* p. 831-836.

Ryder, G., and Spudis, P. D. (1980) Volcanic rocks in the lunar highlands. In *Proc. Conf. Lunar Highlands Crust* (J. J. Papike and R. B. Merrill, eds.). Pergamon Press, New York, p. 353-375.

Ryder, G., and Taylor, G. J. (1976) Did mare volcanism commence early in lunar history? *Proc. Lunar Sci. Conf. 7,* p. 1741-1755.

Ryder, G., and Wood, J. A. (1977) Serenitatis and Imbrium impact melts: implications for large-scale layering in the lunar crust. *Proc. Lunar Sci. Conf. 8,* p. 655-668.

Schaber, G. G. (1973) Lava flows in Mare Imbrium: geologic evaluation from Apollo orbital photography. *Proc. Lunar Sci. Conf. 4,* p. 73-92.

Schaber, G. G., Boyce, J. M., and Moore, H. J. (1976) The scarcity of mappable flow lobes on the lunar maria: unique morphology of the Imbrium flows. *Proc. Lunar Sci. Conf. 7,* p. 2783-2800.

Schmidt, R. M., and Holsapple, K. A. (1980) Theory and experiments on centrifuge cratering. *J. Geophys. Res.* 85:235-252.

Schultz, P. H. (1976a) *Moon Morphology.* University of Texas Press, Austin.

Schultz, P. H. (1976b) Floor-fractured lunar craters. *The Moon* 15:241-273.
Schultz, P. H., and Gault, D. E. (1979) Atmospheric effects on martian ejecta emplacement. *J. Geophys. Res.* 84:7669-7687.
Schultz, P. H., and Gault, D. E. (1985) Clustered impacts: experiments and implications. *J. Geophys. Res.* 90:3701-3732.
Schultz, P. H., and Mendell, W. (1978) Orbital infrared observations of lunar craters and possible implications for impact ejecta emplacement. *Proc. Lunar Planet. Sci. Conf.* 9, p. 2857-2883.
Schultz, P. H., and Spencer, J. (1979) Effects of substrate strength on crater statistics: implications for surface ages and gravity scaling. *Lunar Planet. Sci.* **X** p. 1081-1083.
Schultz, P. H., and Spudis, P. D. (1979) Evidence for ancient mare volcanism. *Proc. Lunar Planet. Sci. Conf. 10*, p. 2899-2918.
Schultz, P. H., and Spudis, P. D. (1983) The beginning and end of lunar mare volcanism. *Nature* 302:233-236.
Schultz, P. H., and Spudis, P. D. (1985) Procellarum basin: a major impact or the effect of Imbrium? *Lunar Planet. Sci.* **XVI:** 746-747.
Schultz, P. H., and Srnka, L. J. (1980) Cometary collisions on the Moon and Mercury. *Nature* 284:22-26.
Schultz, P. H., Greeley, R., and Gault, D. (1977) Interpreting statistics of small lunar craters. *Proc. Lunar Sci. Conf. 8*, p. 3539-3564.
Schultz, P. H., Orphal, D., Miller, B., Borden, W. F., and Larson, S. A. (1981) Multi-ring basin formation: possible clues from impact cratering calculations. In *Multi-ring Basins* (P. H. Schultz and R. B. Merrill, eds.). *Proc. Lunar Planet. Sci. 12A*, p. 181-196.
Sharpton, V. L., and Head, J. W. (1982) Stratigraphy and structural evolution of southern Mare Serenitatis: a reinterpretation based on Apollo Lunar Sounder Experiment data. *J. Geophys. Res.* 87:10983-10998.
Shervais, J. W., Taylor, L. A., and Lindstrom, M. M. (1985) Apollo 14 mare basalts: petrology and geochemistry of clasts from consortium breccia 14321. Proc. Lunar Planet. Sci. Conf. 15, in *J. Geophys. Res.* 90:C375-C395.
Shirley, D. N. (1983) A partially molten magma ocean model. Proc. Lunar Planet. Sci. Conf. 13, in *J. Geophys. Res.* 88:A519-A527.
Shirley, D. N., and Wasson, J. T. (1981) Mechanism for the extrusion of KREEP. *Proc. Lunar Planet. Sci. Conf. 12B*, p. 965-987.
Shoemaker, E. M. (1965) Preliminary analysis of the fine structure of Mare Cognitum. JPL Technical Report 32-700, Jet Propulsion Laboratory, Pasadena, Calif., p. 75-133.
Shoemaker, E. M., Morris, E. C., Batson, R., Holt, H. E., Larson, K., Montgomery, D., Rennilson, J., and Whitaker, E. (1969) Television observations from Surveyor. In *Surveyor Program Results.* NASA Special Paper 184. National Aeronautics and Space Administration, Washington, D.C., 19-128.
Short, N. M., and Forman, M. L. (1972) Thickness of impact crater ejecta on the lunar surface. *Mod. Geology* 3:69-91.
Silver, L. T. (1971) U-Th-Pb isotope systems in Apollo 11 and 12 regolithic materials and a possible age for the Copernican impact. *EOS* 52:535.
Soderblom, L. A. (1970) A model for small-impact erosion applied to the lunar surface. *J. Geophys. Res.* 75:2655-2661.
Soderblom, L. A., and Lebofsky, L. (1972) Technique for rapid determination of relative ages of lunar areas from orbital photography. *J. Geophys. Res.* 77:279-296.
Solomon, S. C., and Head, J. W. (1979) Vertical movement in mare basins: relation to mare emplacement basin tectonics and lunar thermal history. *J. Geophys. Res.* 84:1667-1682.
Solomon, S. C., and Head, J. W. (1980) Lunar mascon basins: lava filling, tectonics, and evolution of the lithosphere. *Rev. Geophys. Space Phys.* 18:107-141.
Sonett, C. P., Smith, B. F., Colburn, D. S., Schubert, G., and Schwartz, K. (1972) The induced magnetic field of the moon: conductivity profiles and inferred temperature. *Proc. Lunar Sci. Conf.* 3, p. 2309-2356.
Spudis, P. D. (1978) Composition and origin of the Apennine Bench Formation. *Proc. Lunar Planet. Sci. Conf.* 9, p. 3379-3394.
Spudis, P. D. (1984) Apollo 16 site geology and impact melts: implications for the geologic history of the lunar highlands. Proc. Lunar Planet. Sci. Conf. 15, in *J. Geophys. Res.* 89:C95-C107.
Spudis, P. D., and Hawke, B. R. (1985) The Apennine Bench Formation revisited. *Workshop on the Geology and Petrology of the Apollo 15 Landing Site*, LPI Contr. 581, Lunar and Planetary Institute, Houston, p. 57-59.
Spudis, P. D., Hawke, B. R., and Lucey, P. (1984) Composition of Orientale basin deposits and implications for the lunar basin-forming process. Proc. Lunar Planet. Sci. Conf. 15, in *J. Geophys. Res.* 89: C197-C210.
Srnka, L. J. (1977) Spontaneous magnetic field generation in hypervelocity impacts. *Proc. Lunar Sci. Conf.* 8: p. 785-792.
Stöffler, D. (1981) Cratering mechanics: data from terrestrial and experimental craters and implications for the Apollo 16 site. In *Workshop on Apollo 16.* LPI Technical Report 81-01. Lunar and Planetary Institute, Houston, p. 132-141.
Stöffler, D., Gault, D. E., Wedekind, J. A., and Polkowski, G. (1975) Experimental hypervelocity impact into quartz sand: distribution and shock metamorphism of ejecta. *J. Geophys. Res.* **80:** 4062-4077.
Stolper, E. (1979) Theoretical petrology. *Rev. Geophys. Space Phys.* 17: 761-776.
Strom, R. G, and Woronow, A. (1982) Solar system

cratering populations. *Lunar Planet Sci.* **XIII**: 782-783.

Stuart-Alexander, D. E., and Howard, K. A. (1970) Lunar maria and circular basins—a review. *Icarus* **12**: 440-456.

Sugiura, N., Wu, Y. M., Strangway, D. W., Pearce, G. W., and Taylor, L. A. (1979) A new magnetic paleointensity value for a young lunar glass. *Proc. Lunar Planet. Sci. Conf. 10,* p. 2189-2198.

Taylor, G. J., Warner, R. D., Keil, K., Ma, M.-S., and Schmitt, R. A. (1980) Silicate liquid immiscibility, evolved lunar rocks and the formation of KREEP. *Proc. Conf. Lunar Highlands Crust* (J. J. Papike and R. B. Merrill, eds.). Pergamon Press, New York, p. 339-352.

Taylor, L. A., Shervais, J. W., Hunter, R. H., Shih, C.-Y., Wooden, J., Nyquist, L. E., and Laul, J. C. (1983) Pre-4.2 AE mare-basalt volcanism in the lunar highlands. *Earth Planet. Sci. Lett.* **66**: 33-47.

Taylor, S. R. (1975) *Lunar Science: A Post-Apollo View.* Pergamon Press, New York.

Taylor, S. R. (1982) *Planetary Science: A Lunar Perspective.* Lunar and Planetary Institute Press, Houston.

Tera, F., Papanastassiou, D. A., and Wasserburg, G. J. (1974) Isotopic evidence for a terminal lunar cataclysm. *Earth Planet. Sci. Lett.* **22**: 1-21.

Thompson, T. W., Zisk, S. H., Shorthill, R. W., Schultz, P. H., and Cutts, J. A. (1981) Lunar craters with radar bright ejecta. *Icarus* **46**: 201-225.

Thomsen, J. M., Austin, M. G., Ruhl, S. F., and Schultz, P. H. (1979) Calculational investigation of impact cratering dynamics: early time material motions. *Proc. Lunar Planet. Sci. Conf. 10*, p. 2741-2756.

Toksoz, M. N., Dainty, A. M., Solomon, S. C., and Anderson, K. (1973) Velocity structure and evolution of the moon. *Proc. Lunar Sci. Conf.* 4, p. 2529-2547.

Toksoz, M. N., Dainty, A. M., Solomon, S. C., and Anderson, K. (1974) Structure of the moon. *Rev. Geophys. Space Phys.* 12: 539-567.

Toksoz, M., Press, F., Dainty, A., Anderson, K., Latham, G., Ewing, M., Dorman, J., Lammlein, D., Sutton, G., and Duennebier, F. (1972) Structure, compositions and properties of lunar crust. *Proc. Lunar Sci. Conf.* 3, p. 2527-2544.

Trask, N. J. (1966) Size and spatial distribution of craters estimated from Ranger photographs. JPL Technical Report 32-800, Jet Propulsion Laboratory, Pasadena, Calif., p. 252-263.

Trask, N. J., and McCauley, J. F. (1972) Differentiation and volcanism in the lunar highlands: photogeologic evidence and Apollo 16 implications. *Earth Planet Sci. Lett.* **14**:201-206.

Walker, D. (1983a) New developments in magmatic processes. *Rev. Geophys. Space Phys.* **21**:1372-1384.

Walker, D. (1983b) Lunar and terrestrial crust formation. Proc. Lunar Planet. Sci. Conf. 14, in *J. Geophys. Res.* **88**: B17-B25.

Warner, J. L., Phinney, W. C., Bickel, C. E., and Simonds, C. H. (1977) Feldspathic granulitic impactites and pre-final bombardment lunar evolution. *Proc. Lunar Sci. Conf.* 8: p. 2051-2066.

Warren, P. H. (1985) The magma ocean concept and lunar evolution. *Ann. Rev. Earth Planet. Sci.* **13**:201-240.

Warren, P. H., and Wasson, J. T. (1979) The origin of KREEP. *Rev. Geophys. Space Phys.* **17**:73-88.

Warren, P. H., and Wasson, J. T. (1980) Early lunar petrogenesis, oceanic and extraoceanic. In *Proc. Conf. Lunar Highlands Crust* (J. J. Papike and R. B. Merrill, eds.). Pergamon press, New York, p. 81-99.

Whitaker, E. (1981) The lunar Procellarum basin. In *Multi-ring Basins* (P. H. Schultz and R. B. Merrill, eds.). *Proc. Lunar Planet. Sci. 12A*, p. 105-111.

Wilhelms, D. E. (1976) Secondary impact craters of lunar basins. *Proc. Lunar Sci. Conf.* 7, p. 2883-2901.

Wilhelms, D. E. (1984) Moon. In *The Geology of the Terrestrial Planets* (M. H. Carr, ed.). NASA SP-469. U.S. Government Printing Office, Washington, D. C., p. 107-205.

Wilhelms, D. E. (1985) Unmanned spaceflights needed as scientific preparation for a manned lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.). Lunar and Planetary Institute Press, Houston, p. 245-252.

Wilhelms, D. E. (in press) *The Geologic History of the Moon.* U.S. Geological Survey Professional Paper 1348.

Wilhelms, D. E., Oberbeck, V. R., and Aggarwal, H. R. (1978) Size-frequency distributions of primary and secondary lunar impact craters. *Proc. Lunar Planet. Sci. Conf.* 9, p. 3735-3762.

Wilson, L., and Head, J. W. (1981) Ascent and eruption of basaltic magma on the Earth and Moon. *J. Geophys. Res.* **86**:2971-3001.

Winzer, S. R., Nava, D. F., Schuhmann, P. J., Lum, R. K. L., Schuhmann, S., Lindstrom, M. M., Lindstrom, D. J., and Philpotts, J. A. (1977) The Apollo 17 "melt sheet": chemistry, age and Rb/Sr systematics. *Earth Planet. Sci. Lett.* **33**:389-400.

Wiskerchen, M. J., and Sonett, C. P. (1977) A lunar metal core? *Proc. Lunar Sci. Conf.* 8, p. 515-535.

Wood, J. A. (1973) Bombardment as a cause of the lunar asymmetry. *The Moon* **8**:73-103.

Wood, J. A., Dickey, J. S., Marvin, U. B., and Powell, B. N. (1970) Lunar anorthosites and a geophysical model of the Moon. In *Proc. Apollo 11 Lunar Sci. Conf.* Pergamon Press, New York, p. 965-988.

Woronow, A., Strom, R. G., and Gurnis, M. (1982) Interpreting the cratering record: Mercury to Ganymede and Callisto. In *Satellites of Jupiter.* University of Arizona Press, Tucson, p. 237-276.

Yoder, C. F. (1981) The free librations of a dissipative moon. *Phil. Trans. Royal Soc. London Ser. A* **303**:327-338.

Young, R. A. (1975) Mare crater size-frequency distributions: implications for relative surface ages and regolith development. *Proc. Lunar Sci. Conf.* 6, p. 2645-2662.

Young, R. A. (1977) The lunar impact flux, radiometric age correlation, and dating of specific lunar features. *Proc. Lunar Sci. Conf.* 8, p. 3457-3473.

Young, R. A. (1984) Quantitative effects of sun angle variations on crater diameter measurements and lunar mare age determinations. *Lunar Planet. Sci.* **XV**:953-954.